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An investigation of the effect of keyways on the torsional strength of shafting

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AN INVESTIGATION OF THE EFFECT OF KEYWAYS ON THE TORSIONAL STRENGTH OF SHAFTING

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THIS IS TO CERTIFY THAT THE THESIS PREPARED UNDER MY SUPERVISION BY

Leroy Morrell Dunsheath and Carlysle Pemberton

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IS APPROVED BY ME AS FULFILLING THIS PART OF THE REQUIREMENTS FOR THE

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AN INVESTIGATION OF THE EFFECT OF
KEYWAYS ON THE TORSIONAL
STRENGTH OF SHAFTING.

AN INVESTIGATION OF THE EFFECT OF KEYWAYS ON THE TORSIONAL STRENGTH OF SHAFTING

I. Introduction.

A considerable amount of data on the strength of keys is available. The several types have been standardized thru a wide range of service and loading. On the other hand, the investigation of the effect of keyways on the strength of shafts has been almost entirely neglected, no data being given on the subject in any of the various handbooks.

Some work along this line has been done, during the past two years, by the Department of Theoretical and Applied Mechanics of the University of Illinois. Two series of tests, showing the effect of keyways on the torsional strength of shafts, and one series of tests showing the effect of keyways on the combined torsional and bending strength of shafts, have been completed.

The object of this series of tests is to supplement the work already done on the effect of keyways on the torsional strength of shafts and to extend the investigations to shafts of other diameters and keyways of different forms than have heretofore been tested.

II. Theory.

The theory involved in shafts of circular cross-section under stress is fairly simple but, when the section is distorted by keyways, mathematical difficulties are introduced which have not, as yet been overcome. It is obvious, however, that a keyway, tho of small sectional area, reduces the strength

of a shaft to a marked degree, due to the fact that the metal has been removed from the portion of the section where the fiber stress is a maximum.

For mechanical reasons, a shaft becomes very unsatisfactory when its elastic limit has been exceeded. For this reason, the elastic limits of the shafts have been chosen as the basis of comparison. The value used is the point on the stress diagram termed by Johnson* the apparent elastic limit. It is the point on the diagram where a line, having a slope, referred to the vertical, one and one-half times as great as the slope of the stress curve below the elastic limit. The value thus obtained is greater than the value of the elastic limit as usually defined, that is the unit stress at which the increase in angular deflection ceases to be proportional to the increase in load but it is more accurately determined and serves fully as well as a basis of comparison.

In these tests the elastic limit of the various sections having keyways are expressed in terms of the elastic limit of the solid section on the same shaft, as per cent. The percentage thus obtained may then be termed the efficiency of the shaft at the particular section. A solid section was tested on each shaft in order to reduce as much as possible the errors due to the inequalities of the steel in the various shafts.

III. Test Pieces.

Three sizes of shafts were tested; cold rolled, 2" and 2½"; and turned, 1-15/16". The shafts were about 5' long.

* Johnson's "Materials of Construction "pp 18 -20.

The following keyways, or arrangement of keyways, were cut in the shafts tested.

1. Solid Section.
2. Standard Square.
3. Standard Long.
4. Deep.
5. Flat.
6. Round.
7. One Direction.
8. Two Standards at 90°.
9. Two Standards at 180°.
10. Four Standards at 90°.

The sketches attached (Figure 1 to Figure 22 inclusive) give the dimensions of the above for the several sizes of shafts. All keyways, with the exception of the standard long, were 7" in length, including the slope at both ends. The standard long was 24" in length, including slope. All keyways were cut to the same width. The keyway adopted as standard (Figures1, 5, 7, 8, 9, 10, 14, 18, 20, 21, and 22) is the one generally accepted in the American practice, its dimensions being one fourth the diameter of the shaft in width and one eighththe diameter of the shaft in depth. The deep keyway (Figures6 and 19) had a depth of three sixteenths of the diameter of the shaft. The depth of the flat keyway (Figures 2, 11, and 15) was taken from"Kent's Pocket-book", page 977, table II. The round keyway (Figures 3, 12, and 16) had a semicircular cross-section, the radius being one eighth of the diameter of the shaft. The one direction keyway (Figures 4, 13, and 17)

had for the lengths of its sides one eighth, and seven thirty-seconds of the diameter of the shaft, the sides forming a right angle.

The keyways were cut at intervals of 90° around the shaft, one inch of solid stock being left between each adjacent pair. Each shaft had four keyways cut in it, with the exception of those containing the long keyway. These latter had two only. Besides these a solid section was left in each shaft.

All tests were made in duplicate. The diameter and material of the shafts were:

2" Standard Cold -rolled steel,---- Tests 1 to 6 inclusive.
$1\frac{15}{16}$" Standard turned steel,-------- Tests 7 to 8 inclusive.
$2\frac{1}{2}$" Standard Cold-rolled steel,----- Tests 9 to 14 inclusive.

The shafts, listed below by their test numbers, had the following keyways cut in them.

Numbers 1, 2, 7, 8, 9, 10,	Standard.
	Flat.
	One Direction.
	Round.
Numbers 3, 4, 11, 12,	Standard Long.
	Deep.
Numbers 5, 6, 13, 14,	Standard.
	Two Standards at 90°.
	Two Standards at 180°.
	Four Standards at 90°.

IV. Apparatus.

All shafts were tested on a 230,000 inch-pound Olsen Torsion Machine in the Laboratory of Applied Mechanics of the

University of Illinois.

The method of indication of twisting deformation is shown by an accompanying photograph (Figure 23). The apparatus consisted of an adjustable iron clamp, carrying a wooden arm about three feet long. The iron clamp was provided with a V shaped recess and a set screw for clamping to the shaft. Mirrors, carrying scales, were attached to half of these arms while the other half carried pointers eight inches long.

V Method of Procedure.

The shaft was clamped in the jaws of the machine. Indicators were placed, eight inches apart, in the solid sections left between the keyways, an indicator bearing a scale and one bearing two pointers, alternating. It can be seen that one indicator bearing two pointers may be made to serve two sections. The adjustment was such that, when stress was applied the pointers would travel over the scales.

An initial load of 1000 inch-pounds was first put on the shaft and the indicator readings taken. The load was then increased and the various deflections recorded. After each increase the load was reduced to 1000 inch-pounds and the initial readings checked. These operations were repeated for increasing increments of load, always returning to 1000 inch-pounds between loads, until all the sections had been carried past their elastic limit. By always returning to 1000 inch-pounds and taking readings, it could be easily determined between what two loads a section took a permanent set. When it was certain that all sections had taken a set, the indicators were removed and the shaft was

stressed to rupture, the final load and approximate deflection, were recorded. Set readings were not taken for the last six tests. It was customary in this series, to approach the desired load at high speed and then use the low speed when adjusting the beam. When the load was taken off, high speed was used until the zero load was passed and then the machine was reversed and the 1000 inch-pounds approached on low speed.

VI. Derivation of Constants.

Unit Stress in Outer Fiber

S -- Unit shearing stress.

Pp -- Twisting moment in inch-pounds -- the load.

d -- Diameter of shaft in inches.

c -- Distance from axis to extreme fiber -- d/2.

J -- Polar moment of inertia for the cross-section $\pi d^4/32$ for circular section (Merriman, Page 228)

$S = Ppc/J = 16Pp/\pi d^3 = 5.1Pp/d^3$

$S = 0.637Pp$ for 2" shafts.

$S = 0.702Pp$ for 1-15/16" shafts.

$S = 0.326Pp$ for $2\frac{1}{2}$" shafts.

Deflection in Degrees per Inch of Length.

Length of arm = 37"

Circumference of circle described by pointer

$$2\pi r = 2 \times 3.14 \times 37 = 232"$$

Divisions on scale are 50 to the inch.

Divisions in circle described by pointer. 252 x 50 = 11600.

Degrees per division per inch of length of shaft.

$$\frac{360}{11600 \times 8} = 0.00388 \text{ for 1-15/16" and 2" shafts.}$$

Adding $\frac{1}{4}$" in the case of $2\frac{1}{2}$" shafts.

$$\frac{360}{2 \times 3.14 \times 37.25 \times 50 \times 8} = 0.00386 \text{ for } 2\tfrac{1}{2}\text{" shafts.}$$

VII. Calculations and Curves.

By the aid of the constants, derived above, the load in inch-pounds was converted to unit fiber stress in the outer fiber and the deflection readings to degrees per inch of length of shaft. The data for the tests, as observed and as computed, is given in full on pages 15-29 inclusive. Stress diagrams for the various shafts were drawn and the elastic limits were found in the method previously described. The ratio of the elastic limit of each keyway bearing section to the elastic limit of the solid section on the same shaft was computed, the quotient being the efficiency of the keyway. Pages 28 and 29 contain tables showing the elastic limit and efficiency of each keyway. An average was obtained for each section with a keyway from the duplicate tests.

VIII. Results and Conclusions.

The results of the series of tests are summed up on page 29 Each test, as before stated, was run in duplicate, thereby forming check results. This, however, is inadequate for any great degree of accuracy since, if the two tests do not agree it is difficult to tell in which shaft the fault lies. It has been assumed that the average efficiencies, obtained from the duplicate tests, are approximately correct, although further tests would, obviously, reduce the error.

In the majority of cases the efficiencies check very closely, considering the simplicity of the apparatus. A considerable discrepancy is found in tests 1 and 3. In test 6 the elastic limit of the section containing two standard keyways at 180° is very low, compared with the values obtained

for the elastic limits of other similar sections. This may be due to some defect in the shaft at that place. The remainder of the results are as close as can be expected.

The tests show, in general, that the efficiency of shafts having keyways is greater in turned shafts than in cold-rolled shafts although the elastic limit of the solid section is much lower, and that the effect of keyways decrease in cold-rolled shafts as the diameter increases. The high efficiency in the turned shafts is probably due to the fact that the keyway in the cold-rolled shaft cuts out a section of the strongest fibers of the shaft, while the turned shafts, being of uniform quality, the effect is not so great.

It is very evident that the shaft with the keyway is weaker than the solid section. It appears that this should be taken into account in the design of shafting, especially cold-rolled shafting with more than one keyway.

The elastic limit of the solid section of the turned shafting was much lower than that of the cold rolled owing to the effect of cold rolling on the outer fiber.

The elastic limit of the solid section of the larger cold rolled shafts was higher than that of the smaller shafts. This was probably due to the fact that the cold-rolled fibers were farther from the axis.

Variations in quality of material in each shaft made accurate determinations of efficiency of shafts with keyways an impossibility. It is easy to see this variation as the last six shafts were cut from one long piece and the elastic limit of the solid portions tested vary considerably.

There is a formula derived from previous tests at the University of Illinois by Herbert F. Moore in bulletin number 42 of the University of Illinois Engineering Experiment Station, for the efficiency of cold rolled shafts.

The formula is:

$$e = 1.0 - 0.2w - 1.1h.$$

where e -- efficiency of shaft with keyway.

w -- width of keyway ÷ diameter of shaft.

h -- depth of keyway ÷ diameter of shaft.

For the standard keyways in our tests, this works out to be,

$$e = 0.8125 \text{ or } 81.25\%$$

This compares very favorably with our results although it is a little low.

Dimensions and Efficiency of Keyways.

(2" cold rolled shafts)

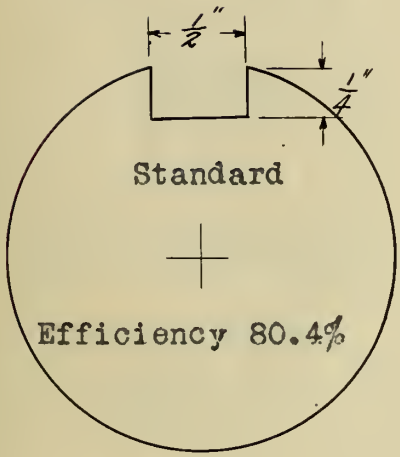


Fig. 1.

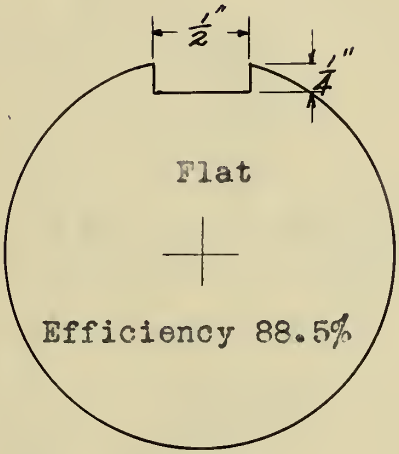


Fig. 2.

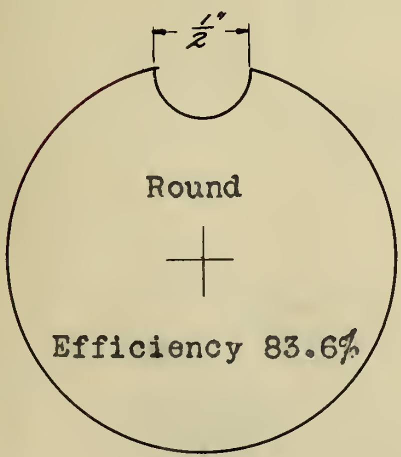


Fig. 3.

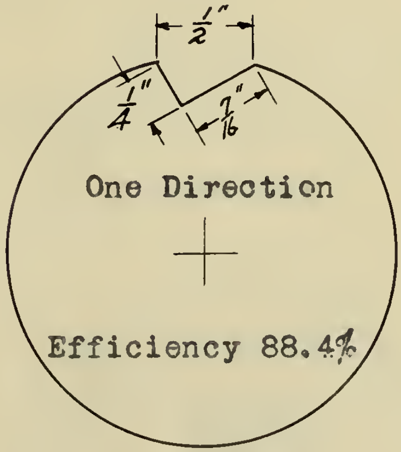


Fig. 4.

Dimensions and Efficiency of Keyways.

(2" cold rolled shafts)

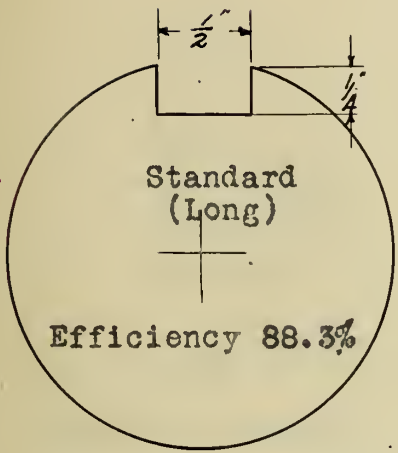


Fig. 5.

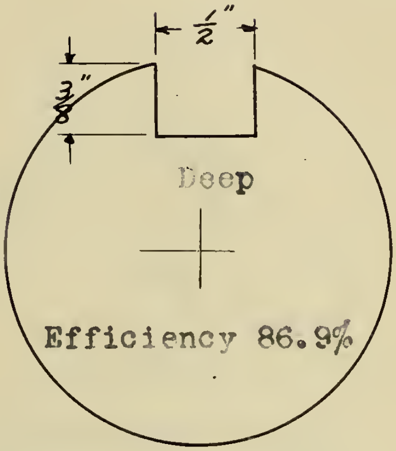


Fig. 6.

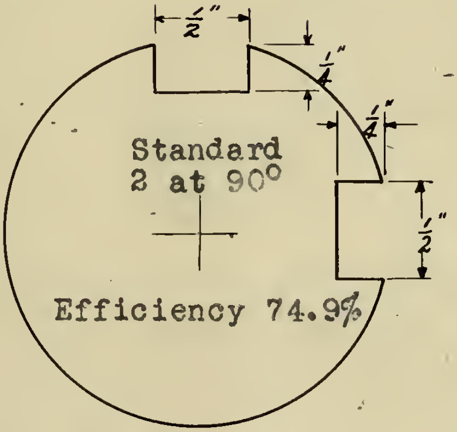


Fig. 7.

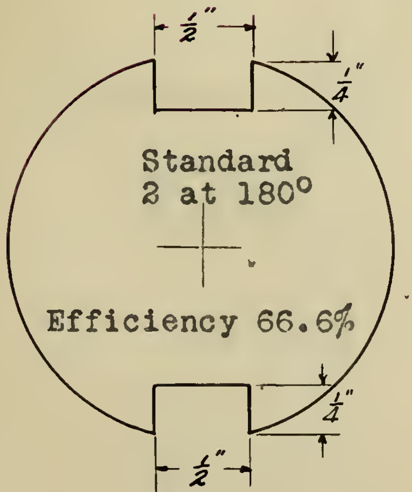


Fig. 8.

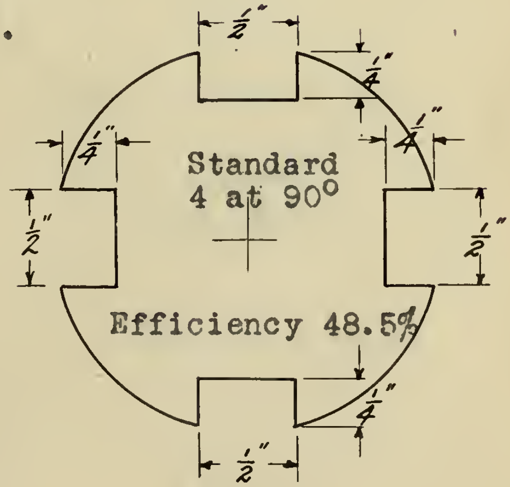


Fig. 9.

Dimensions and Efficiency of Keyways.

(1-15/16" turned shafts)

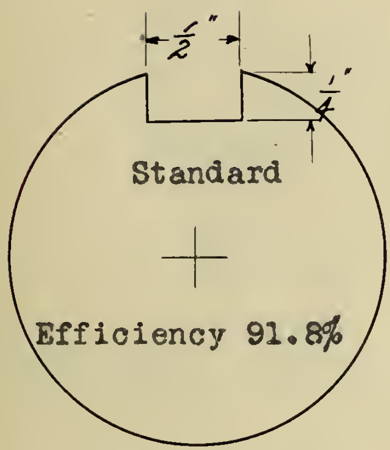


Fig. 10.

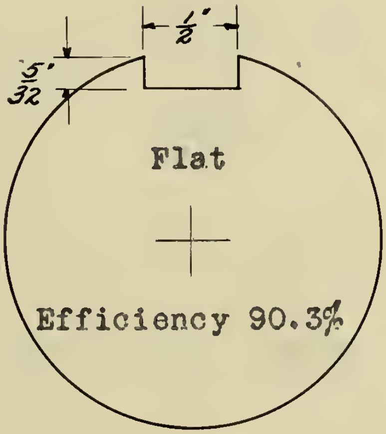


Fig. 11.

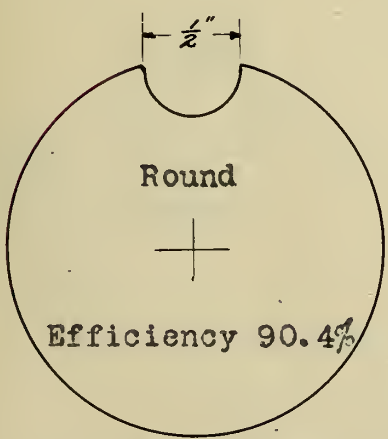


Fig. 12.

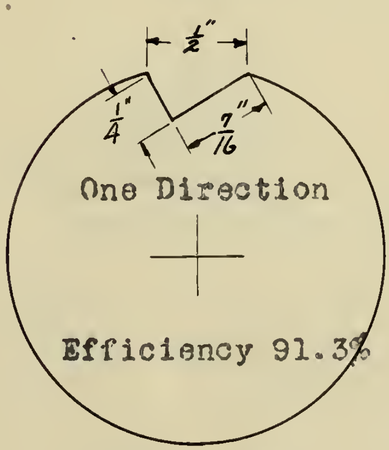


Fig. 13.

Dimensions and Efficiency of Keyways.

($2\frac{1}{2}$" cold rolled shafts)

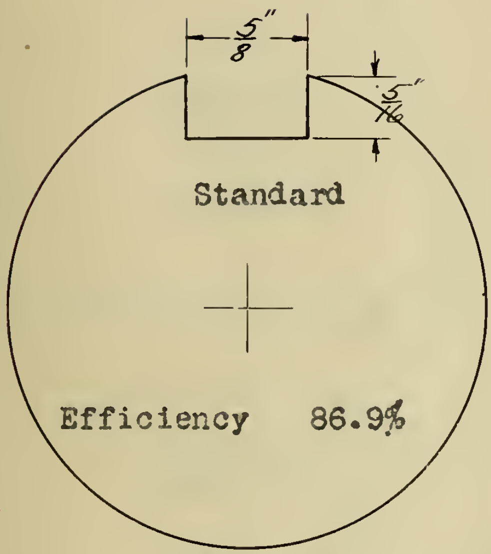


Fig. 14.

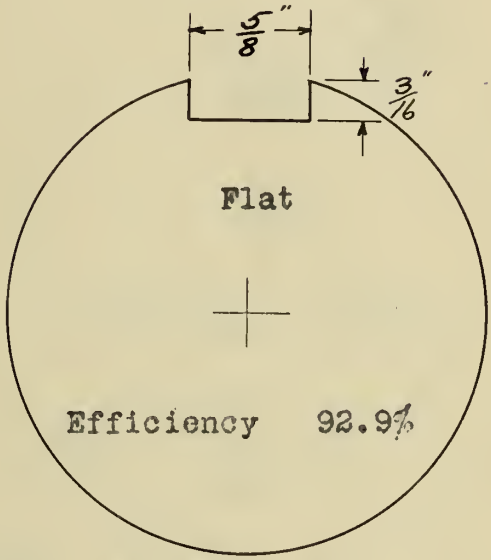


Fig. 15.

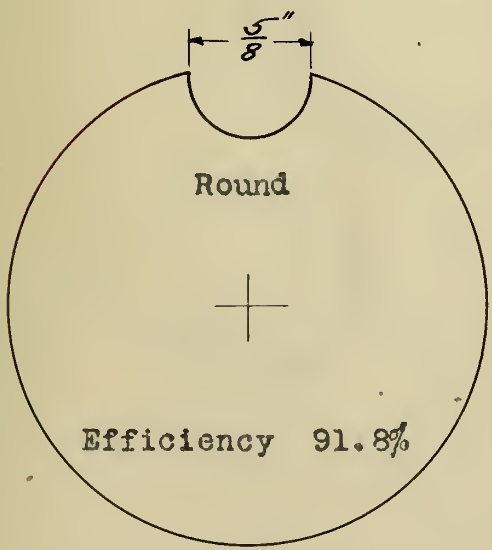


Fig. 16.

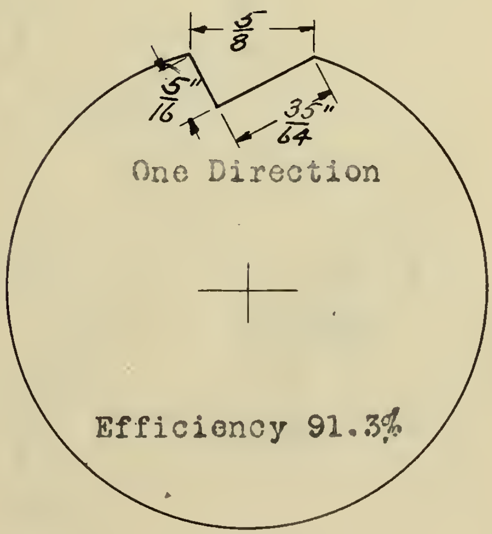


Fig. 17.

Dimensions and Efficiency of Keyways.

(2½" cold rolled shafts)

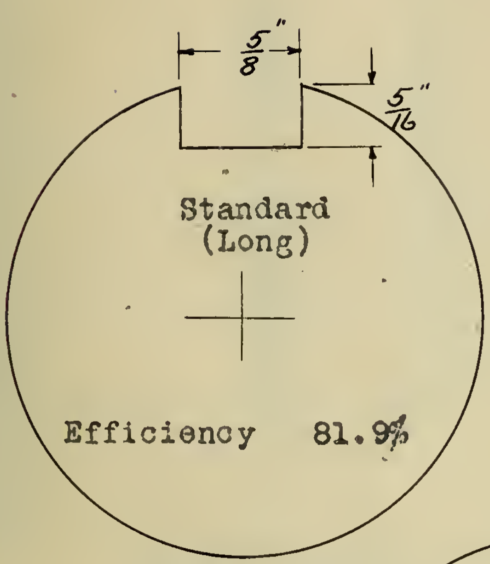


Fig. 18.

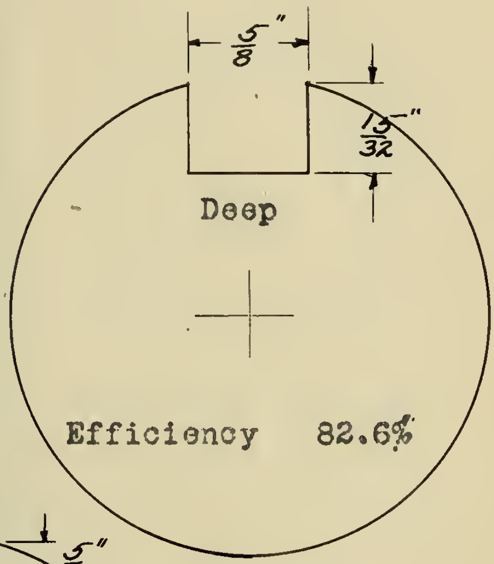


Fig. 19.

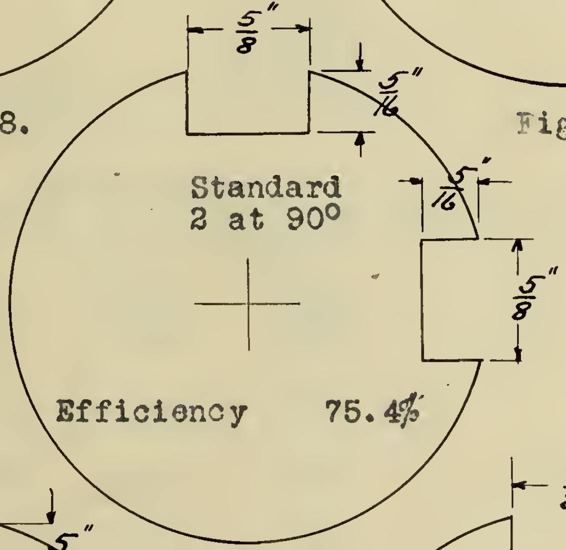


Fig. 20.

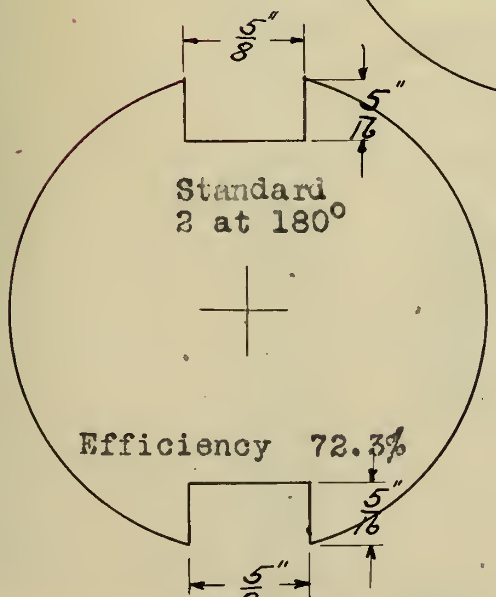


Fig. 21.

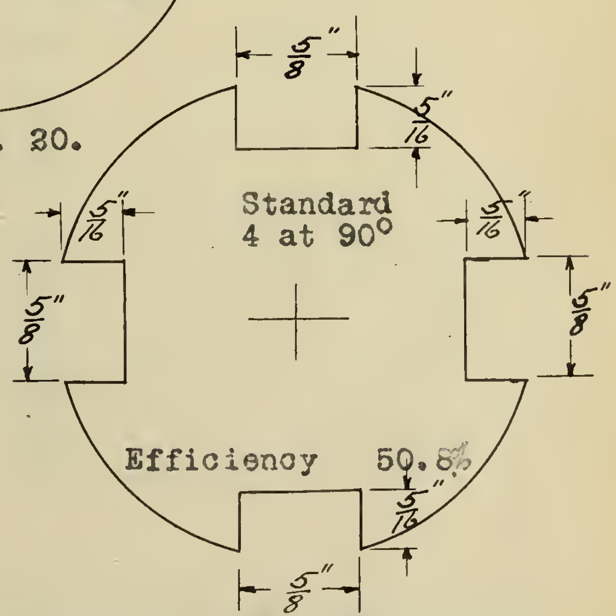


Fig. 22.

Actual Data.

Test No. 1.

Actual Scale Readings.

Load	Solid	Deep	Standard Long
1700	138	173	69
10500	130	163	83
1700	138	173	69
20000	121	152	110
1700	138	173	69
29200	112	141	129
1700	138	173	69
36300	107	131	145
1700	138	173	69
43000	101	120	161
1700	138	173	69
46300	98	112	171
1700	138	168	72
49000	97	105	180
1700	138	163	73
51500	92.5	91	193
1700	138	153	86
53800	91	75	210
1700	138	148	88
61900			80
1700			131.5
66000			66
1700			130.5

Maximum -- 80000 inch-pounds

Twist --260°

Computed Results.

Deflections in degrees per inch of length

Stress Outer Fiber	Solid	Deep	Standard Long
1080	.000	.000	.000
6700	.031	.0387	.0503
1080			
12700	.0658	.0735	.159
1080			
18600	.1006	.124	.232
1080			
23100	.12	.163	.294
1080			
27400	.143	.205	.356
1080			
29500	.155	.236	.395
1080		.0194	.0116
31200	.159	.263	.43
1080		.0387	.0155
32800	.178	.317	.441
1080		.0774	.0581
34300	.182	.379	.546
1080			.0736
39400	.224		
1080	.0252		
42000	.378		
1080	.029		

Maximum -- 50900 pounds per square inch.

Actual Data.
Test No. 2.

Actual Scale Readings.

Load	Solid	Standard Long	Deep
1000	185	163	0
8600	176.5	153	10
1000	185	163	0
18000	170	143	20
1000	185	163	0
26500	162	133	30
1000	185	163	0
35800	155	123	40
1000	185	163	0
43800	145	113	50
1000	185	163	0
53000	135	103	61
1000	185	163	1
58600	135	93	76
1000	185	158	10
60200	133	183	128
1000	184.5	143	57
64100	123		
1000	179		
66700	114		
1000	170		

Maximum -- 80000 inch-pounds.
Twist -- 340°

Computed Results.
Deflections in degrees per inch of length

Stress Outer Fiber	Solid	Standard Long	Deep
637	.000	.000	.000
5500	.0329	.0387	.0387
637			
11400	.058	.0774	.0774
637			
16900	.089	.116	.116
637			
22800	.166	.155	.155
637			
27900	.155	.194	.194
637			
33800	.194	.232	.236
637			.00387
37300	.194	.271	.294
637		.0194	.0387
38300	.201	.461	.495
637	.00193	.0774	.221
40800	.24		
637	.0232		
42500	.275		
637	.058		

Maximum -- 50900 pounds per square inch.

Actual Data.
Test No. 3.

Actual Scale Readings.

Load	Solid	Standard	Round	One Direction	Flat
1000	178	143	1	- 10	194
12500	168	130	12	0	183
1000	178	143	1	- 10	194
24000	158	119	25	11	172
1000	178	143	1	- 10	194
33000	149	108	32	22	162
1000	178	143	1	- 10	194
40000	144	100	40	29	155
1000	178	141	1	- 10	194
48000	137	90	50	37	147
1000	178	139	1	- 8	194
55000	130	75	60	48	137
1000	178	132	6	- 5	192
60000	123	53	77	61	125
1000	175	115	18	3	184
63000	116	14	103	79	108
1000	171	83	41	17	171
65500	108	off	144	104	83
1000	160	20	76	40	145
68000	97	off	off	137	47
1000	157	Off	135	70	119

Maximum -- 91500 inch-pounds
Twist -- 920°

Computed Results.
Deflections in degrees per inch of length.

Stress Outer Fiber	Solid	Standard	Round	One Direction	Flat
637	.000	.000	.000	.000	.000
7950	.0387	.0503	.0425	.0387	.0426
15400	.0774	.093	.093	.0813	.0852
21000	.112	.135	.12	.124	.124
25500	.132	.166	.151	.151	.151
		.00774			
30600	.159	.205	.19	.182	.182
		.0155		.00774	
35000	.186	.263	.228	.224	.221
		.0425	.0194	.0194	.00774
38200	.213	.348	.294	.275	.267
	.0116	.108	.066	.0503	.0387
40200	.24	.50	.395	.344	.294
	.0271	.271	.151	.105	.089
41700	.272		.553	.441	.430
	.07	.476	.29	.194	.19
43300	.314		.519	.57	.57
					.29

Maximum -- 58250 pounds per square inch.

Actual Data.
Test No. 4.

Actual Scale Readings.

Load	Solid	Standard	Round	One Direction	Flat
1000	140	195	8	25	170
12500	130	184	20	36	161
1000	140	196	8	26	171
22000	121	173	30	46	152
1000	140	196	8	26	171
30500	113	164	39	54	143
1000	140	195	8	26	171
39500	105	155	48	63	134
1000	140	195	9	26	171
46500	100	140	57	71	127
1000	140	194	11	26	170
54500	91	123	71	82	115
1000	138	185	17	31	167
58000	86	112	83	90	106
1000	137	173	20	35	162
62500	80	75	106	108	90
1000	134	141	44	48	151
66000	71	70	145	130	67
1000	129	77	77	67	131
66500	62				26
1000	131		147	102	94

Maximum -- 84400 inch-pounds
Twist -- 410°

Computed Results.
Deflections in degrees per inch of length

Stress Outer Fiber	Solid	Standard	Round	One Direction	Flat
637	.000	.000	.000	.000	.000
7950	.0387	.0426	.0465	.0426	.0348
14000	.0735	.0852	.0852	.0735	.062
19400	.105	.12	.12	.112	.104
25800	.136	.155	.155	.128	.143
			.00387		
29600	.155	.213	.19	.178	.167
		.00387	.0116		
34700	.19	.279	.244	.221	.213
	.00774	.0387	.0348	.0232	.0116
36900	.209	.321	.29	.252	.248
	.0116	.0852	.0465	.0387	.031
39800	.232	.465	.38	.321	.31
	.0232	.209	.139	.089	.0735
42000	.267	.484	.53	.406	.399
	.0426	.457	.457	.143	.112
42300	.302				.558
	.0271			.298	.294

Maximum -- 53800 pounds per square inch.

Actual Data.

Test No. 5.

Actual Scale Readings.

Load	Solid 7"long	4 Std. at 90°	2 Std. at 180°	2 Std. at 90°(8½")	Standard
1000	10	9	195	169	5
9000	16	23	183	158	13
1000	10	9	195	169	5
15000	21	37	176	151	19
1000	10	9	195	169	5
21000	25	47	168	144	27
1000	10	11	195	169	5
28000	31	64	160	135	35
1000	10	15	195	169	5
34000	35	90	151	127	41
1000	10	29	193	167	5
38500	38	134	143	120	46
1000	10	65	190	167	5
44000	42		130	110	54
1000	10		185	163	6
47500	46		108	94	61
1000	10		169	153	8
52000	49		77	73	70
1000	10		141	137	12
56500	54				
1000	11				
61000	61				
1000	15				

Maximum -- 81000 inch-pounds
Twist -- 890°

Computed Results.

Deflection in degrees per inch of length

Stress Outer Fiber	Solid	4 Std. at 90°	2 Std. at 180°	2 Std. at 90°	Standard
637	.000	.000	.000	.000	.000
5700	.0232	.0542	.0465	.0426	.031
9500	.0426	.108	.0735	.0697	.0542
13400	.058	.147 .00774	.1045	.097	.0852
17600	.0814	.213 .0232	.135	.132	.116
21600	.093	.314 .0774	.170 .00774	.163	.139
24500	.108	.523 .217	.201 .0194	.19 .0774	.159
28000	.124		.232 .0774	.228 .0232	.19 .00387
30200	.139		.337 .101	.29 .062	.216 .0116
33100	.151		.457 .209	.372 .124	.252 .0371
36000	.17 .00774				
38800	.198 .0194				

Maximum -- 51600 pounds per square inch.

Actual Data.

Test No. 6.

Load	Solid	4 Std. at 90°	2 Std. at 180°	2 Std. at 90°	Standard
		Actual Scale Readings.			
1000	145	172	- 4	10	191
13000	135	149	11	27	179
1000	145	172	- 4	10	191
16000	132	143	15	25	175
1000	145	172	- 4	10	191
22000	126	130	23	34	169
1000	145	172	- 4	10	191
28500	121	109	32	43	162
1000	145	163	- 4	10	191
36500	113	31	45	55	153
1000	145	108	- 1	10	190
40500	110	Off	53	63	144
1000	145	5	3	11	190
44000	107		65	70	145
1000	145		10	15	189
48000	104		87	85	140
1000	145		27	27	187
52000	100		166	132	123
1000	145		98	66	183
56000	95				118
1000	144			133	176
59000	90				94
1000	141				157

Maximum -- 76000 inch-pounds
Twist -- 790°

Computed Results.

Deflection in degrees per inch of length

Stress Outer Fiber	Solid	4 Std. at 90°	2 Std. at 180°	2 Std. at 90°	Standard
637	.000	.000	.000	.000	.000
8300	.0387	.089	.058	.0658	.0465
10400	.0502	.108	.0735	.058	.0619
14000	.0735	.167	.104	.093	.085
18300	.093	.244	.139	.128	.112
		.0348			
23200	.128	.545	.190	.174	.147
		.248	.0116		
25800	.135	.625	.221	.205	.182
			.0271	.0038	.00387
28000	.147		.267	.232	.178
			.054	.0193	.00774
30600	.159		.352	.29	.197
			.12	.0658	.0155
33100	.174			.29	.263
				.0217	.031
35700	.193				.282
	.00387			.48	.058
37600	.213				.375
	.0155				.135

Maximum -- 48400 pounds per square inch.

Actual Data.
Test No. 7.

Actual Scale Readings.

Load	Solid	Standard	Round	One Direction	Flat
1000	2	167	- 7	189	144
12000	12	155	4	178	132
1000	2	167	- 7	188	144
22000	21	143	15	167	122
1000	2	167	- 7	188	144
30000	28	130	26	158	113
1000	2	161	- 4	185	141
32500	30	- 15	60	144	97
1000	3	15	30	173	127
33800	33		142	127	75
1000	3		110	159	108
33900	37			36	
1000	8			68	
35000	39				
1000	9			22	
35500	46				
1000	15				
36500	80				
1000	38				

Maximum -- 81800 inch-pounds.
Twist -- 2250°

Computed Results.
Deflection in degrees per inch of length

Stress Outer Fiber	Solid	Standard	Round	One Direction	Flat
700	.000	.000	.000	.000	.000
8400	.0387	.0426	.0425	.0425	.0464
15400	.0737	.093	.085	.085	.085
				.00387	
21000	.101	.143	.128	.12	.12
		.0232	.0116	.0155	.0116
22800	.109	.705	.259	.174	.182
		.552	.143	.0619	.0658
23700	.120		.576	.24	.267
	.00387			.116	.139
23800	.136			.592	
	.0228			.468	
24500	.145				
	.0271			.646	
24900	.171				
	.0502				
25600	.302				
	.139				

Maximum -- 57300 pounds per square inch.

Actual Data.
Test No. 8.

Load	Solid	Standard	Round	One Direction	Flat
	Actual Scale Reading.				
1000	160	9	194	4	139
11500	150	21	183	13	128
1000	160	9	194	4	139
17000	144	26	177	18	123
1000	158	9	193	4	138
21700	140	33	172	24	118
1000	158	10	193	4	138
25000	137	36	167	28	113
1000	157	10	192	5	137
28000	134	40	164	32	111
1000	157	11	192	5	137
31000	130	51	153	40	104
1000	156	30	183	12	133
32000	128	87	139	47	98
1000	156	54	170	17	128
33500	123			89	45
1000	152			56	79
34000	120			133	
1000	149			99	
36500	91				
1000	123				

Maximum -- 83300 inch-pounds
Twist -- 2470°

Computed Results.
Deflection in degrees per inch of length

Stress Outer Fiber	Solid	Standard	Round	One Direction	Flat
700	.000	.000	.000	.000	.000
8050	.0387	.0464	.0425	.0348	.0425
11900	.0619	.0658	.0658	.0542	.062
15200	.0774	.0928	.085	.0774	.0813
		.0038	.0038		.0038
17500	.089	.100	.105	.0928	.100
	.0116	.0038	.0077		.0077
19600	.1008	.12	.116	.108	.108
	.0077	.0077	.0038	.0077	
21700	.116	.138	.159	.139	.135
	.0155	.0812	.0425	.031	.0232
22400	.124	.32	.213	.167	.159
	.0155	.174	.0928	.0504	.0425
23500	.143			.329	.364
	.031			.215	.232
23800	.155			.500	
	.0812			.368	
25600	.267				

Maximum -- 58300 pounds per square inch.

Actual Data.
Test No. 9.

Actual Scale Readings.

Load	Solid	Standard Long	Deep
1000	000	11	7
15000	4.5	17	13
38000	12	25	21
56700	18	32	28
65000	21	35	34
75000	24	39	37
87000	27	44	43
93500	29	48	47
101500	32	54	51
107500	34	59	66
119500	41	87	115
122000	44	109	160
125500	46	118	175
135000	61		

Maximum -- 183000 inch-pounds
Twist -- 6150°

Computed Results.
Deflection in degrees per inch of length

Stress Outer Fiber	Solid	Standard Long	Deep
326	.000	.000	.000
5900	.0174	.0232	.0232
12400	.0464	.054	.054
18200	.0695	.081	.081
21200	.081	.0925	.104
24400	.097	.108	.116
28400	.104	.127	.139
30500	.112	.143	.154
32900	.124	.166	.170
35000	.131	.185	.228
39000	.158	.294	.417
39800	.17	.378	.591
41000	.178	.413	.65
44000	.236		

Maximum -- 59700 pounds per square inch.

Actual Data.
Test No. 10.

Actual Scale Readings.

Load	Solid	Standard Long	Deep
1000	5	000	7.5
25000	13	8	17
42500	17	15	24
58000	23	21	31
81600	30	29	40
96500	35	37	49
104000	38	43	58
113500	42	55	80
125000	49	86	145
132500	55	148	
138500	68		
146000	103		

Maximum -- 188000 inch-pounds
Twist -- 790°

Computed Results
Deflection in degrees per inch of length

Stress Outer Fiber	Solid	Standard Long	Deep
326	.000	.000	.000
8200	.0293	.0310	.0386
13900	.0463	.058	.0656
18900	.0695	.0811	.0887
26600	.0965	.102	.127
31400	.116	.143	.162
33900	.127	.166	.197
37000	.143	.212	.274
40800	.170	.332	.533
43200	.193	.572	
45200	.243		
47600	.376		

Maximum -- 61300 pounds per square inch.

Actual Data.

Test No. 11.

Actual Scale Reading.

Load	Solid	STandard	2 Std. at 90°	2 Std. at 180°	4 Std. at 90°
1000	- 8	12	179	173	33
17500	- 3	18	173	167	42
1000	- 8	12	178	173	33
29000	0	22	168	161	47
1000	- 8	12	178	173	33
40000	4	26	163	158	54
1000	- 8	12	178	173	33
50000	7	30	159	154	60
1000	- 8	12	178	173	34
62500	11	35	155	148	69
1000	- 8	12	178	173	36
72500	14	39	150	144	82
1000	- 8	12	178	173	43
83000	17	42	145	139	108
1000	- 8	12	178	172	62
91000	20	47	139	132	176
1000	- 8	14	175	170	123
99500	22	50	134	127	off
1000	- 8	15	172	166	off
105000	24	53	127	121	
115000	26	57	114	107	
117500	29	65	88	83	
123000	32	73	44	41	
1000	- 6	29	95	96	
127300	35				

Maximum -- 169000 inch-pounds

Twist -- 685°

Computed Results.

Deflection in degrees per inch of length.

Stress Outer Fiber	Solid	Standard	2 Std. at 90°	2 Std. at 180°	4Std. at 90°
326	.000	.000	.000	.000	.000
5700	.0193	.0232	.0232	.0232	.0348
9400	.0309	.0386	.0425	.0463	.054
13000	.0463	.054	.0617	.0579	.081
16300	.0579	.0695	.0772	.0733	.104
					.00386
20400	.0734	.0887	.0926	.0965	.139
					.0116
23600	.085	.104	.112	.112	.189
					.0386
27100	.0965	.116	.131	.131	.29
					.112
29700	.108	.135	.155	.158	.552
		.0772	.0155	.0116	.348
32400	.116	.147	.174	.177	
		.0116	.0232	.027	
34200	.124	.158	.239	.239	
36300	.131	.174	.251	.253	
38300	.143	.205	.351	.348	
40100	.155	.236	.521	.510	
	.0772	.0656	.324	.298	
41500	.166				

Maximum -- 55100 pounds per square inch.

Actual Data.
Test No. 12.

Actual Scale Readings.

Load	Solid	Standard	2 Std. at 90°	2 Std. at 180°	4 Std. at 90°
1000	- 8	18	180	175	1
19700	- 4	24	173	169	11
44000	4	33	163	160	24
58000	9	38	157	155	34
64700	11	41	155	152	40
76000	15	45	149	146	60
88000	18	49	143	141	103
95500	21	53	137	135	
102500	23	56	129	126	off
110000	26	61	114	111	
120000	30	71	67	61	
125500	34	81	4		
130500	38	96			
136000	45	124			
140000	55				

Maximum -- 165000 inch-pounds
Twist -- 730°

Computed Results.
Deflection in degrees per inch of length

Stress Outer Fiber	Solid	Standard	2 Std. at 90°	2 Std. at 180°	4 Std. at 90°
3260	.000	.000	.000	.000	.000
6400	.0155	.0232	.027	.0232	.0386
14300	.0463	.0579	.0656	.0579	.0887
18900	.0656	.0772	.0887	.0772	.127
21100	.0733	.0887	.0965	.0887	.151
24800	.0887	.104	.120	.112	.228
27700	.100	.12	.143	.131	.394
31200	.112	.135	.166	.155	
33400	.120	.147	.197	.189	
35800	.131	.166	.255	.247	
39100	.147	.205	.436	.44	
40900	.162	.243	.68		
42500	.178	.301			
44300	.205	.409			
45600	.244				

Maximum -- 53800 pounds per square inch.

Actual Data.
Test No. 13.

Actual Scale Readings.

Load	Solid	Standard	Round	One Direction	Flat
1000	19	5.5	188	178	15
20000	25	12	183	172	21.5
44500	32	21	175	164	30
59500	37	27	170	158	35
80500	44	35	162	151	43
96500	50	42	156	145	48
110500	55	51	149	138	56
121000	61	65	140	129	64
131500	71	104	120	110	83
137500	82	184	84	80	117
143300	91		42	45	156
147700	115				
150600	140				

Maximum -- 198000 inch-pounds
Twist -- 1440°

Computed Results.

Deflection in degrees per inch of length

Stress Outer Fiber	Solid	Standard	Round	One Direction	Flat
326	.000	.000	.000	.000	.000
6500	.0232	.0232	.0193	.0232	.0251
14500	.0502	.068	.0502	.054	.0579
19900	.0695	.081	.0695	.0772	.0772
26600	.0965	.112	.1000	.104	.108
31400	.114	.139	.123	.127	.127
36100	.139	.174	.151	.154	.158
39500	.162	.228	.185	.189	.189
42800	.201	.378	.263	.262	.262
44800	.243	.687	.402	.355	.394
46700	.278		.564	.513	.545
48300	.370				
48200	.467				

Maximum -- 64500 pounds per square inch.

Actual Data.
Test No. 14.

Actual Scale Readings.

Load	Solid	Standard	Round	One Direction	Flat
1000	20	10	177	182	0
23700	27	18	169	175	8
44700	34	26	162	169	15
63500	39	32	156	163	22
77000	45	37	152	158	26.5
87000	48	37	148	155	30
94000	50	45	145	152.5	32.5
106500	55	52	140	147	38
118500	60	64	132	140	45
126000	66	82	121	132	54
131700	72	111	108	120	66
139600	81	179	80	99	89
143700	94	off	37	67	124
147600	111	off	off	13	184
150800	136				

Computed Results.
Deflection in degrees per inch of length

Stress Outer Fiber	Solid	Standard	Round	One Direction	Flat
326	.000	.000	.000	.000	.000
7750	.027	.0309	.0309	.027	.0309
14600	.054	.0618	.058	.0502	.058
20700	.0734	.085	.081	.0734	.085
25300	.0965	.104	.096	.0927	.102
28400	.108	.12	.112	.104	.116
30600	.116	.135	.123	.116	.125
34700	.135	.162	.143	.135	.147
38700	.154	.208	.174	.162	.174
41200	.177	.278	.216	.193	.208
43000	.201	.39	.266	.239	.255
45800	.236	.652	.374	.32	.344
46800	.286		.540	.434	.479
48300	.351			.653	.71
	.448				

No. of Test	Solid	Deep	Standard Long
1	36700	27800	30200
2	36700	35000	35000
9	36800	31400	30500
10	37000	29600	30000

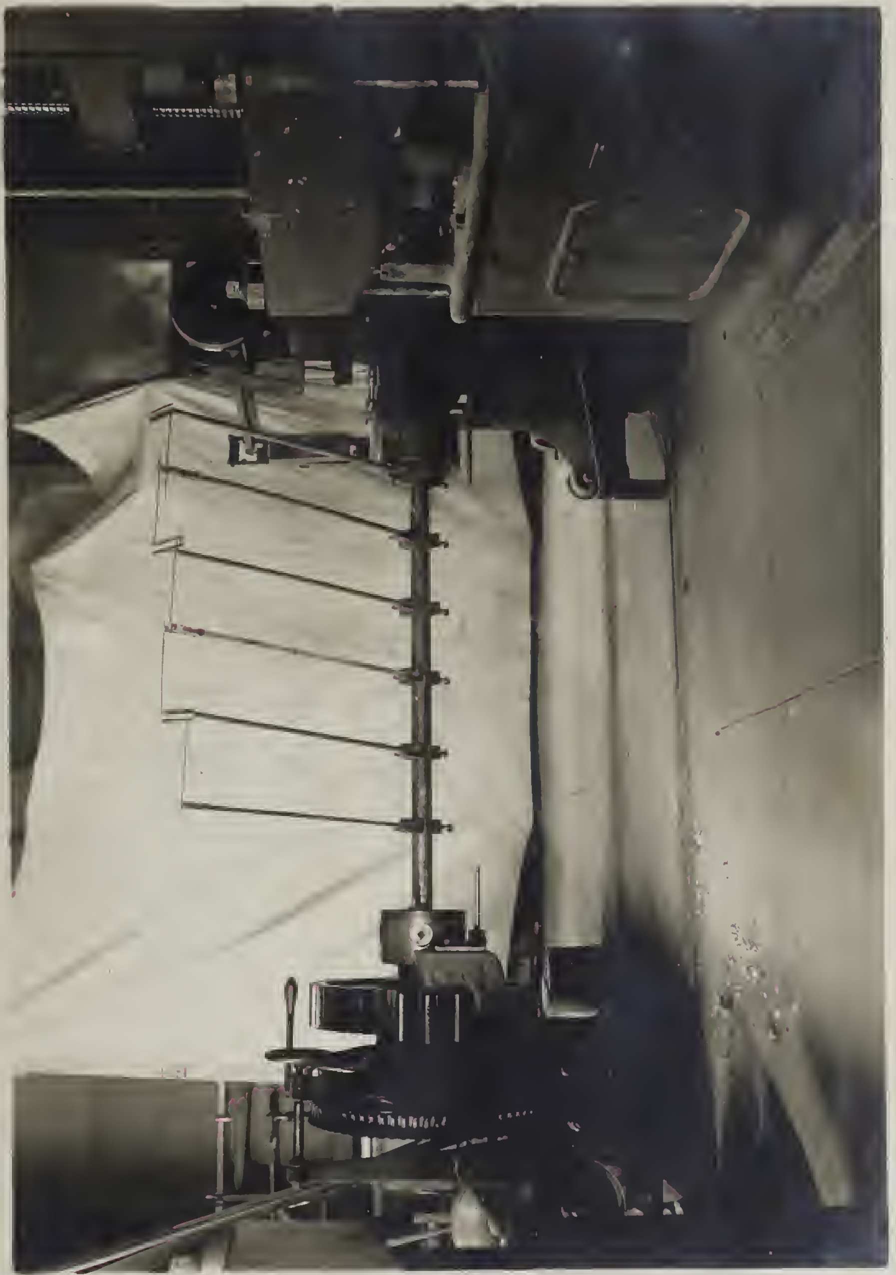
No. of Test	Solid	Standard	Round	One Direction	Flat
3	36600	31000	31900	32500	33200
4	36900	29000	29700	32600	32000
7	21800	19800	19100	19500	19400
8	19500	18100	18200	18200	17900
13	36300	31400	33500	33400	33800
14	37500	31700	34300	34000	34800

No. of Test	Solid	Standard	2 at 90°	2 at 180°	4 at 90°
5	35400	27800	26900	26200	17000
6	37100	29800	27400	22000	18200
11	37800	33400	29000	27900	19400
12	37900	33500	28100	26800	19100

No. of Test	Solid	Std.	Rd.	O.D.	Flat	Deep	Long	2 at 90°	2 at 180°	4 at 90°
1	36700					78.5	81.3			
2	36700					95.4	95.4			
3	36600	84.5	86.9	88.5	90.5					
4	36900	78.5	80.4	88.3	86.6					
5	35400	78.5						76.0	74.0	48.0
6	37100	80.3						73.8	59.3	49.1
7	21800	90.8	87.5	89.3	88.9					
8	19500	92.8	93.3	93.3	91.7					
9	36800					85.3	82.8			
10	37000					80.0	81.0			
11	37800	88.4						76.7	73.9	51.3
12	37900	88.4						74.2	70.7	50.4
13	36300	86.5	92.3	92.0	93.1					
14	37500	84.5	91.4	90.6	92.7					

Average Efficiency.

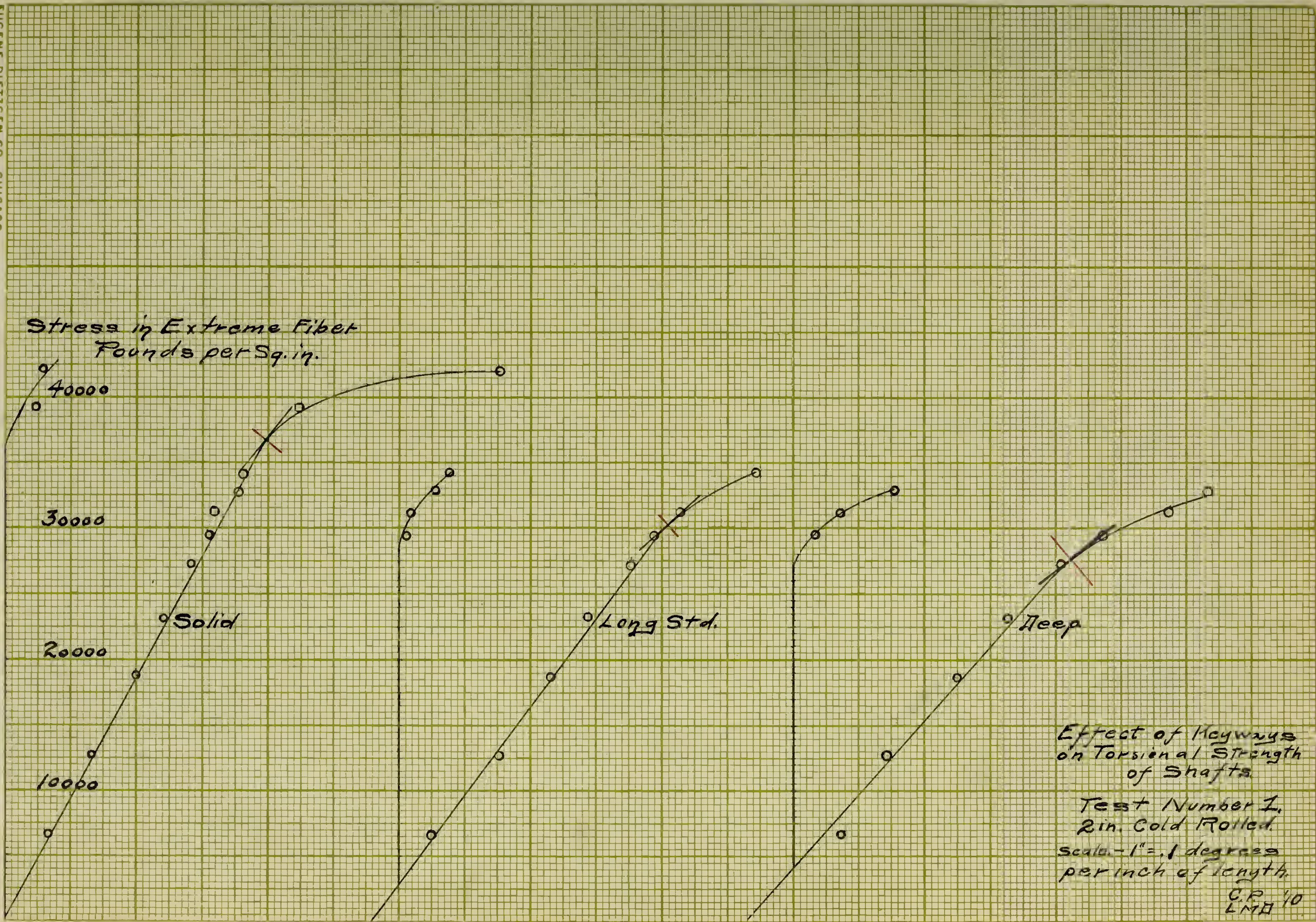
	Cold 2"	Rolled 2½"	Turned 1-15/16"
Standard	80.4	86.9	91.8
Round	83.6	91.8	90.4
One Direct.	88.4	91.3	91.3
Flat	88.5	92.9	90.3
Deep	86.9	82.6	
Long	88.3	81.9	
2 Std. at 90°	74.9	75.4	
2 Std. at 180°	66.6	72.3	
4 Std. at 90°	48.5	50.8	



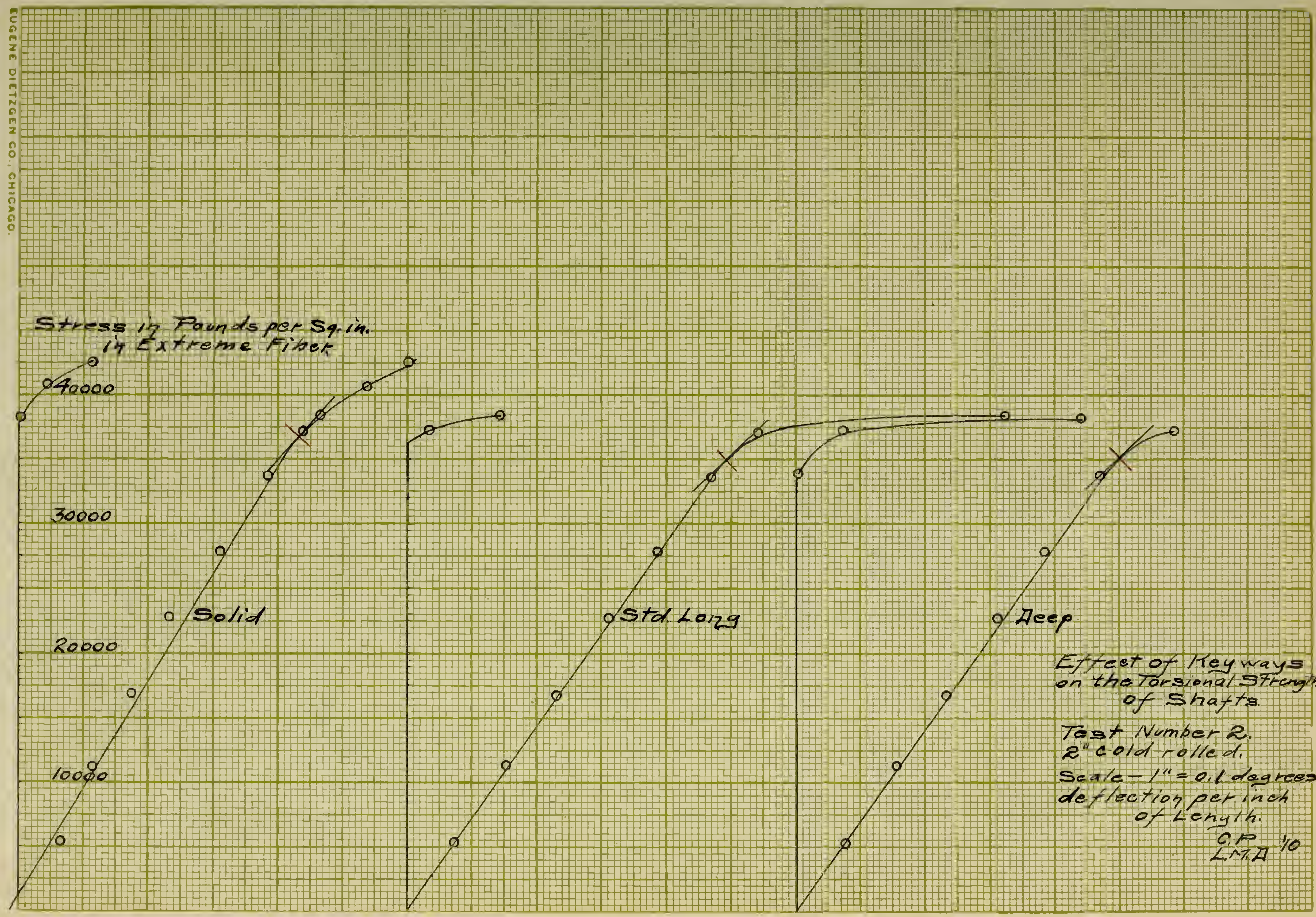
Arrangement of Apparatus

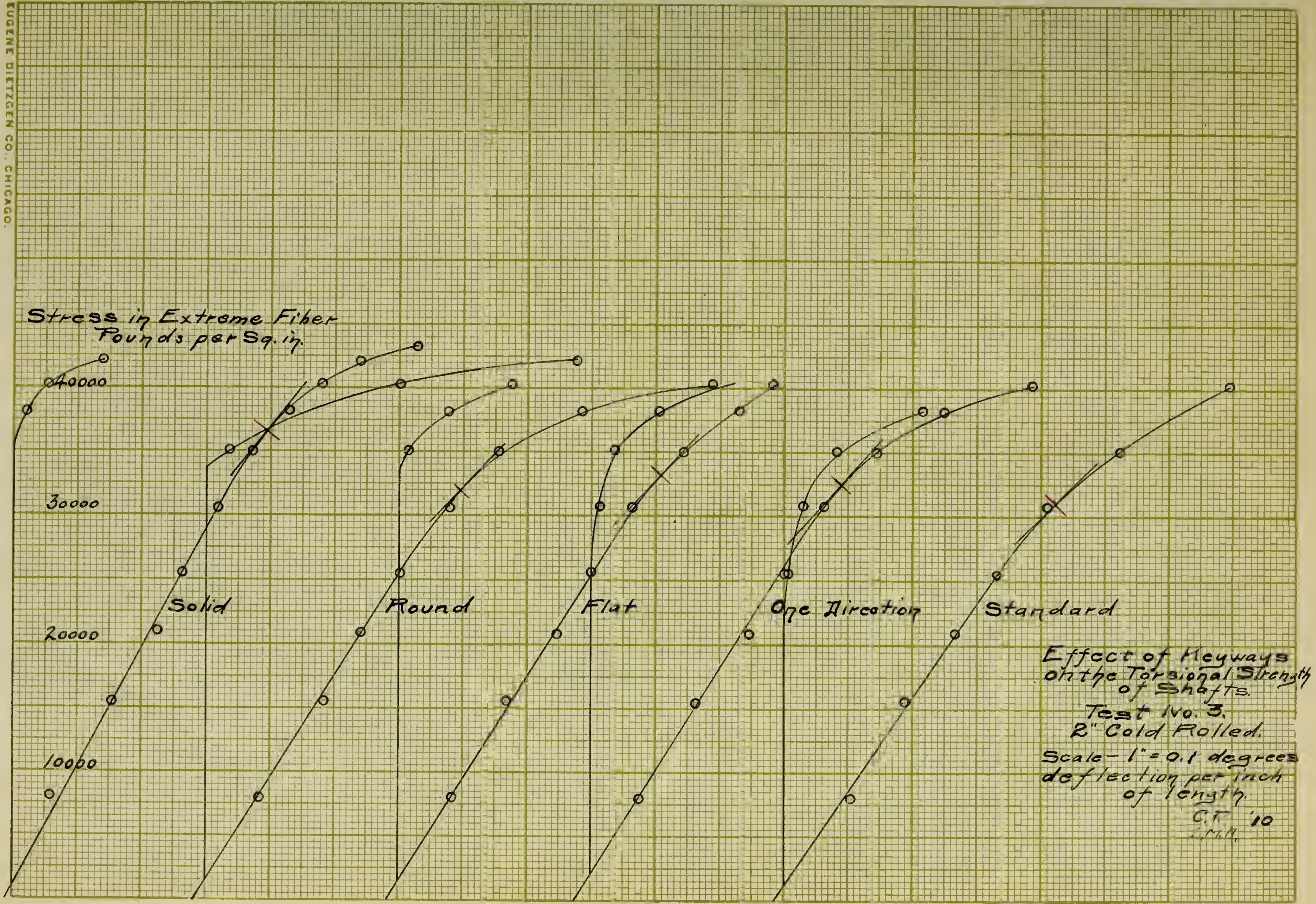
Brittle Ductile

Typical Fractures

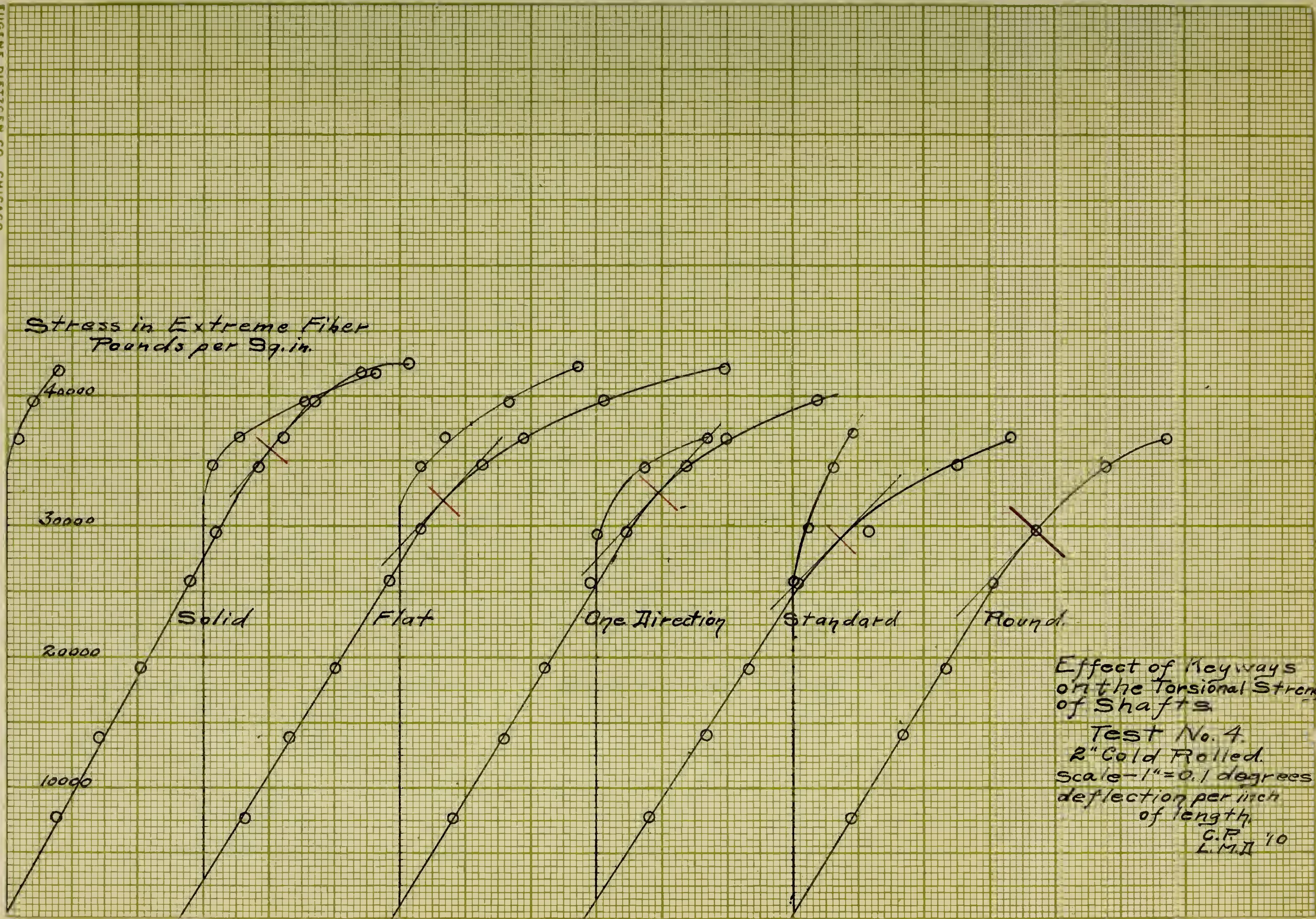


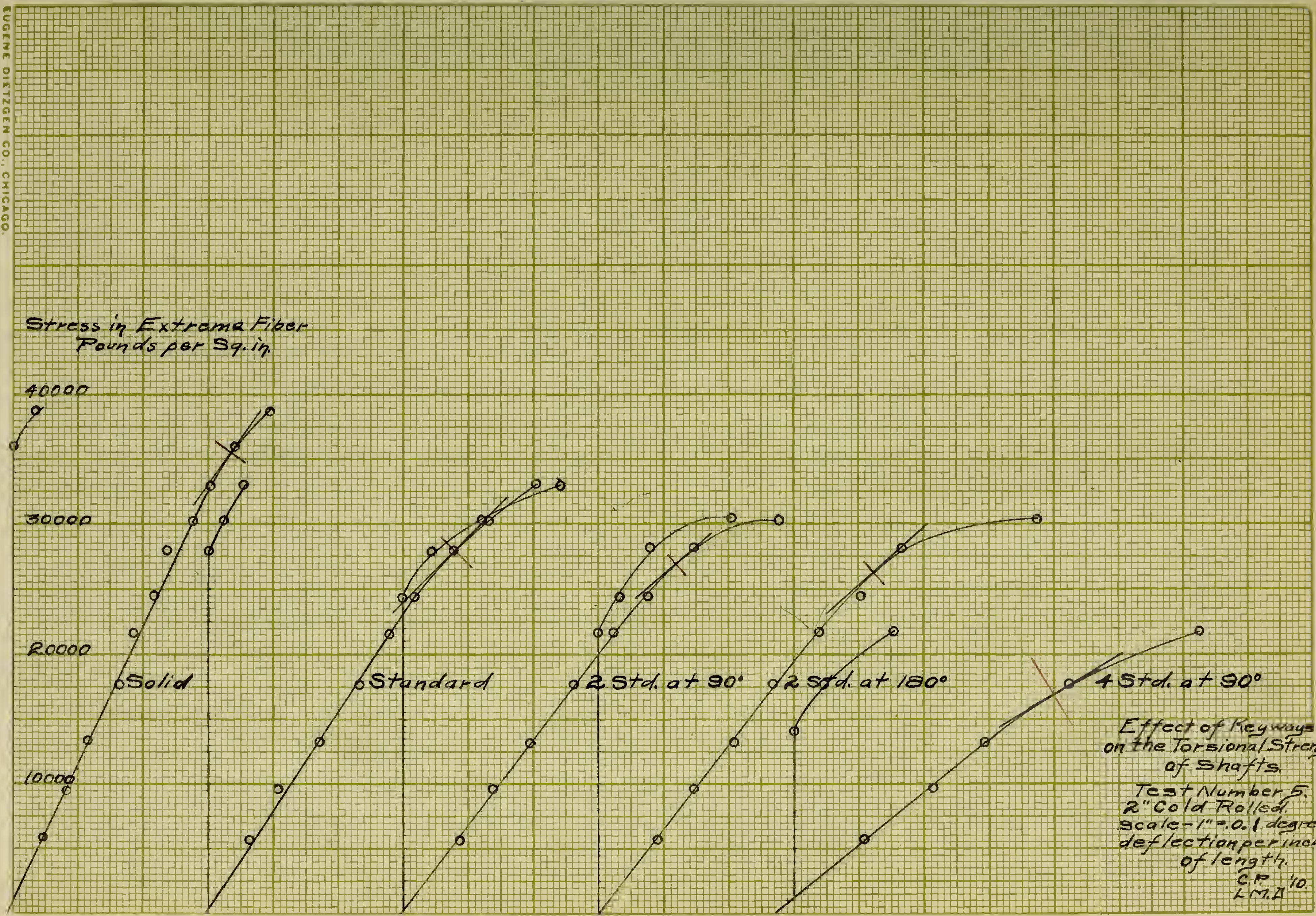
EUGENE DIETZGEN CO., CHICAGO.

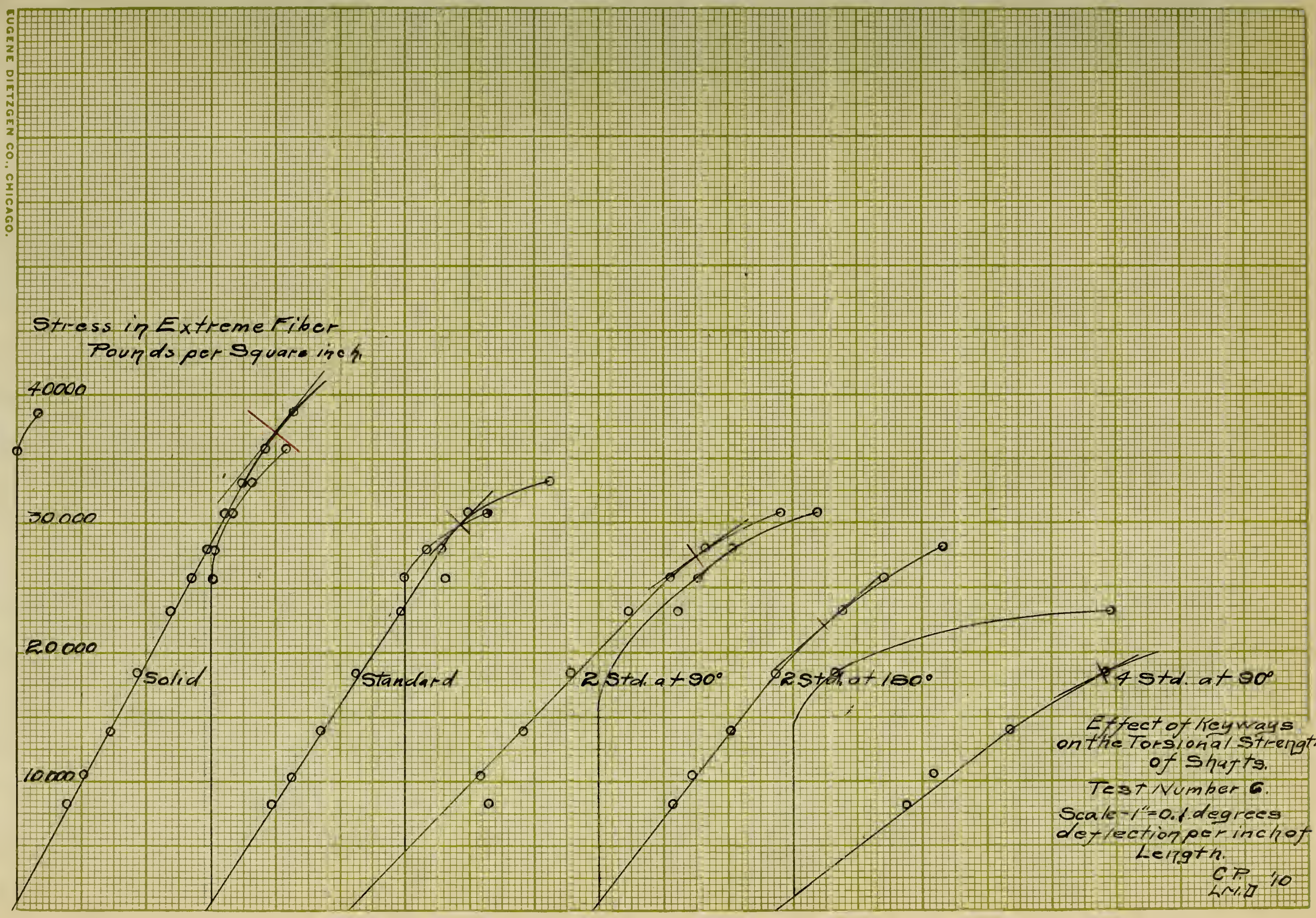

Stress in Pounds per Sq. in.
in Extreme Fiber
40000
30000
20000
10000
Solid
Std. Long
Deep
Effect of Keyways
on the Torsional Strength
of Shafts.
Test Number 2.
2" cold rolled.
Scale - 1" = 0.1 degrees
deflection per inch
of Length.
C.P.
L.M.D. 1/10
EUGENE DIETZGEN CO., CHICAGO.



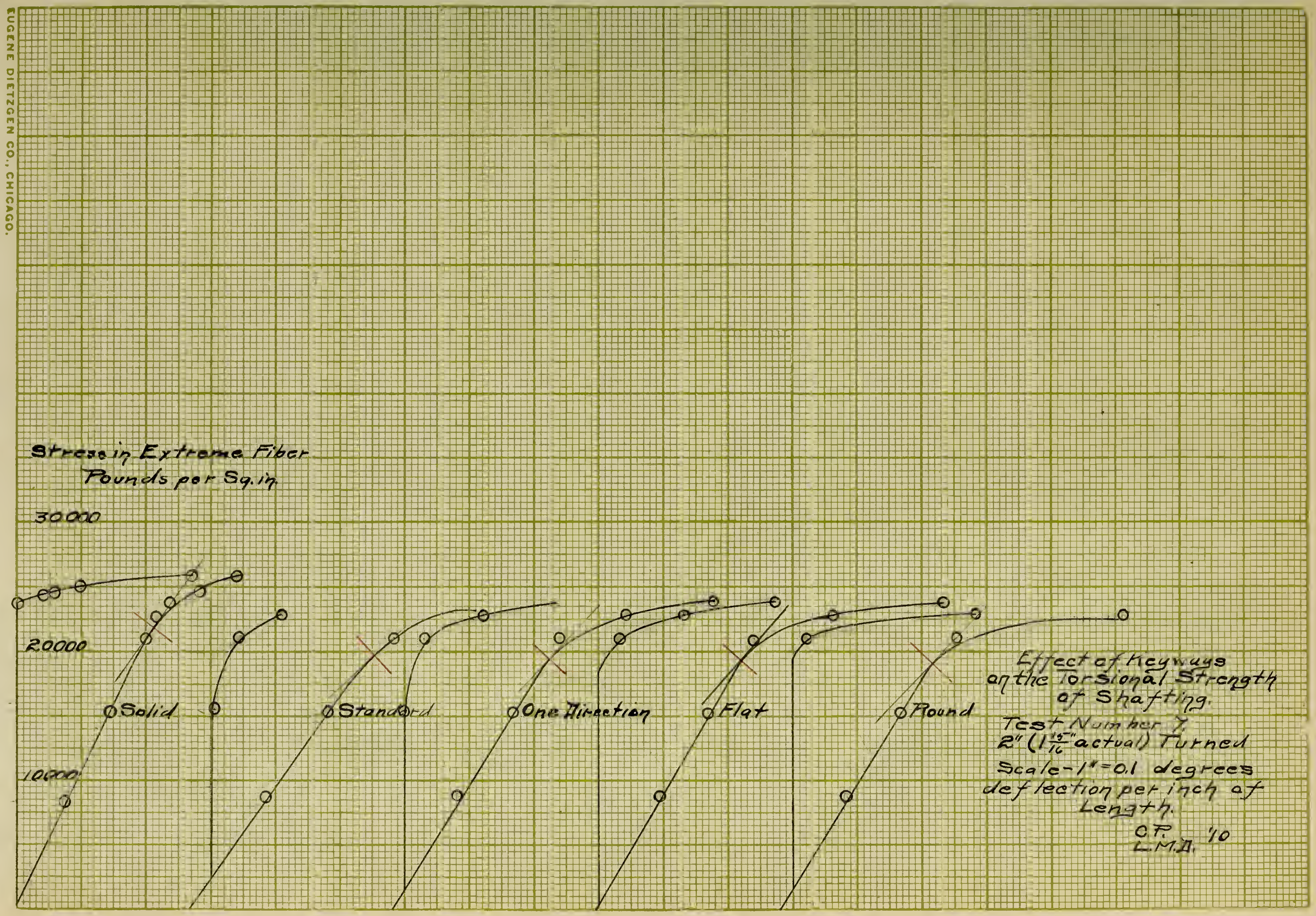
Stress in Extreme Fiber
Pounds per Sq. in.
40000
30000
20000
10000
Solid
Round
Flat
One Direction
Standard
Effect of Keyways
on the Torsional Strength
of Shafts.
Test No. 3.
2" Cold Rolled.
Scale - 1" = 0.1 degrees
deflection per inch
of length.
C.F. '10

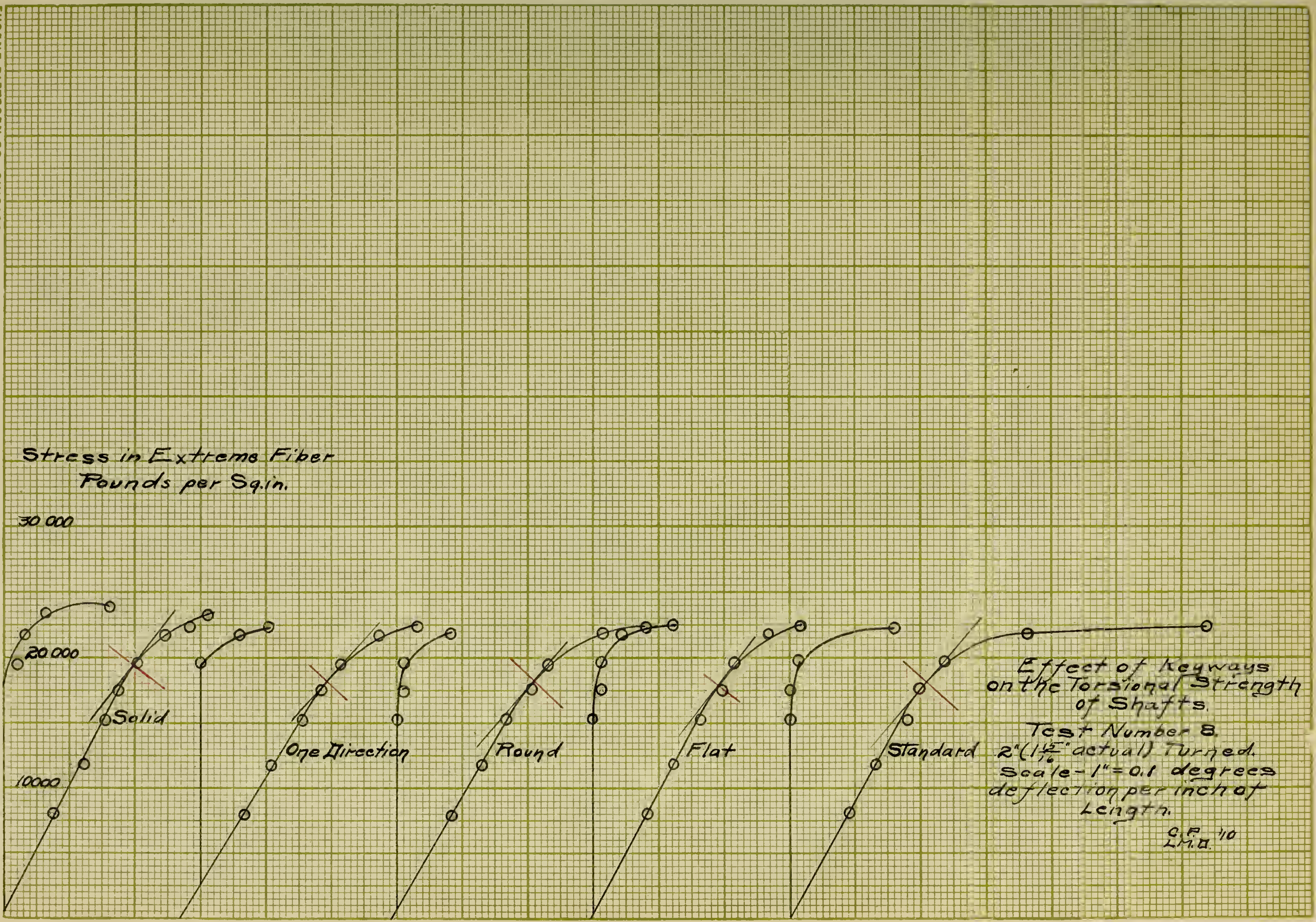

Stress in Extreme Fiber
Pounds per Sq. in.
40000
30000
20000
10000
Solid
Flat
One Direction
Standard
Round.
Effect of Keyways
on the Torsional Strength
of Shafts.
Test No. 4.
2" Cold Rolled.
Scale-1"=0.1 degrees
deflection per inch
of length
C.P.
L.M.D. '10

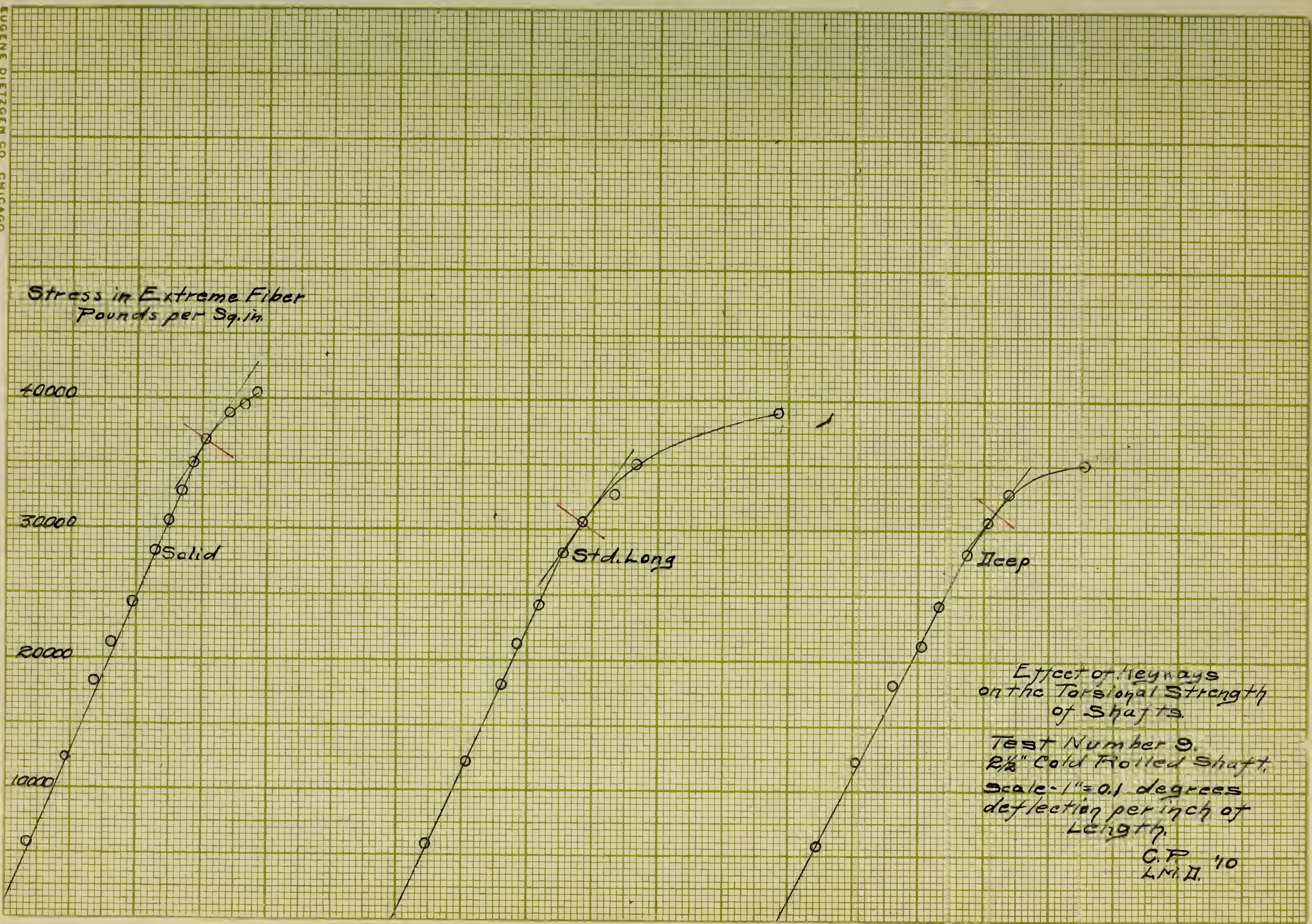

Stress in Extreme Fiber
Pounds per Sq. in.
40000
30000
20000
10000
Solid
Standard
2 Std. at 90°
2 Std. at 180°
4 Std. at 90°
Effect of Keyways
on the Torsional Strength
of Shafts.
Test Number 5.
2" Cold Rolled.
Scale - 1" = 0.1 degrees
deflection per inch
of length.
C.P. '10.
L.M.A.



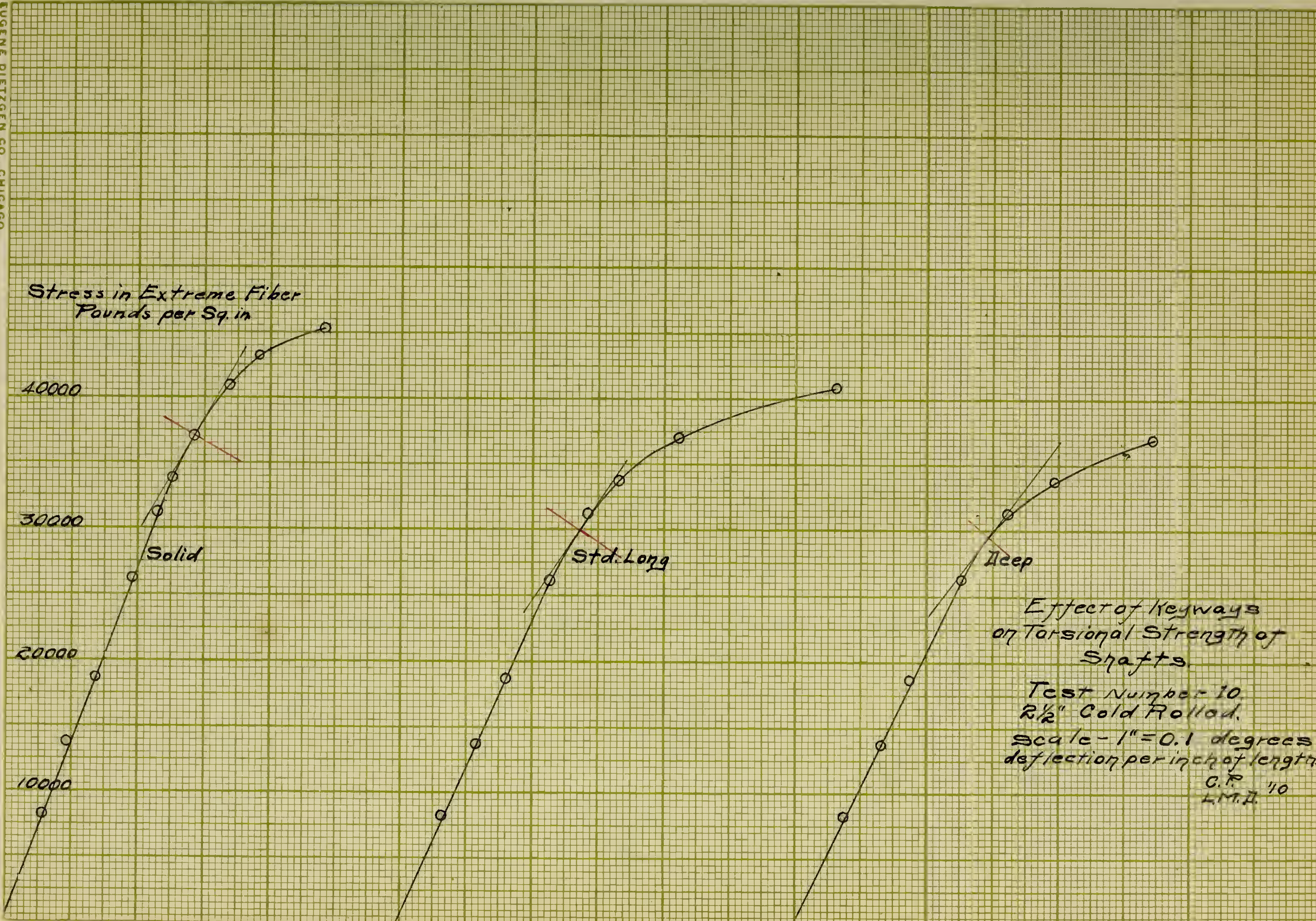
EUGENE DIETZGEN CO., CHICAGO.
Stress in Extreme Fiber
Pounds per Square inch
40000
30.000
20.000
10.000
Solid
Standard
2 Std. at 90°
2 Std. at 180°
4 Std. at 90°
Effect of Keyways
on the Torsional Strength
of Shafts.
Test Number 6.
Scale-1"=0.1 degrees
deflection per inch of
Length.
C.P. '10


Stress in Extreme Fiber
Pounds per Sq. in
30000
20000
10000
Solid
Standard
One Direction
Flat
Round
Effect of Keyways
on the Torsional Strength
of Shafting.
Test Number 7.
2" ($1\frac{15}{16}$" actual) Turned
Scale - 1" = 0.1 degrees
deflection per inch of
Length.
C.P. '10
L.M.D.
EUGENE DIETZGEN CO., CHICAGO.

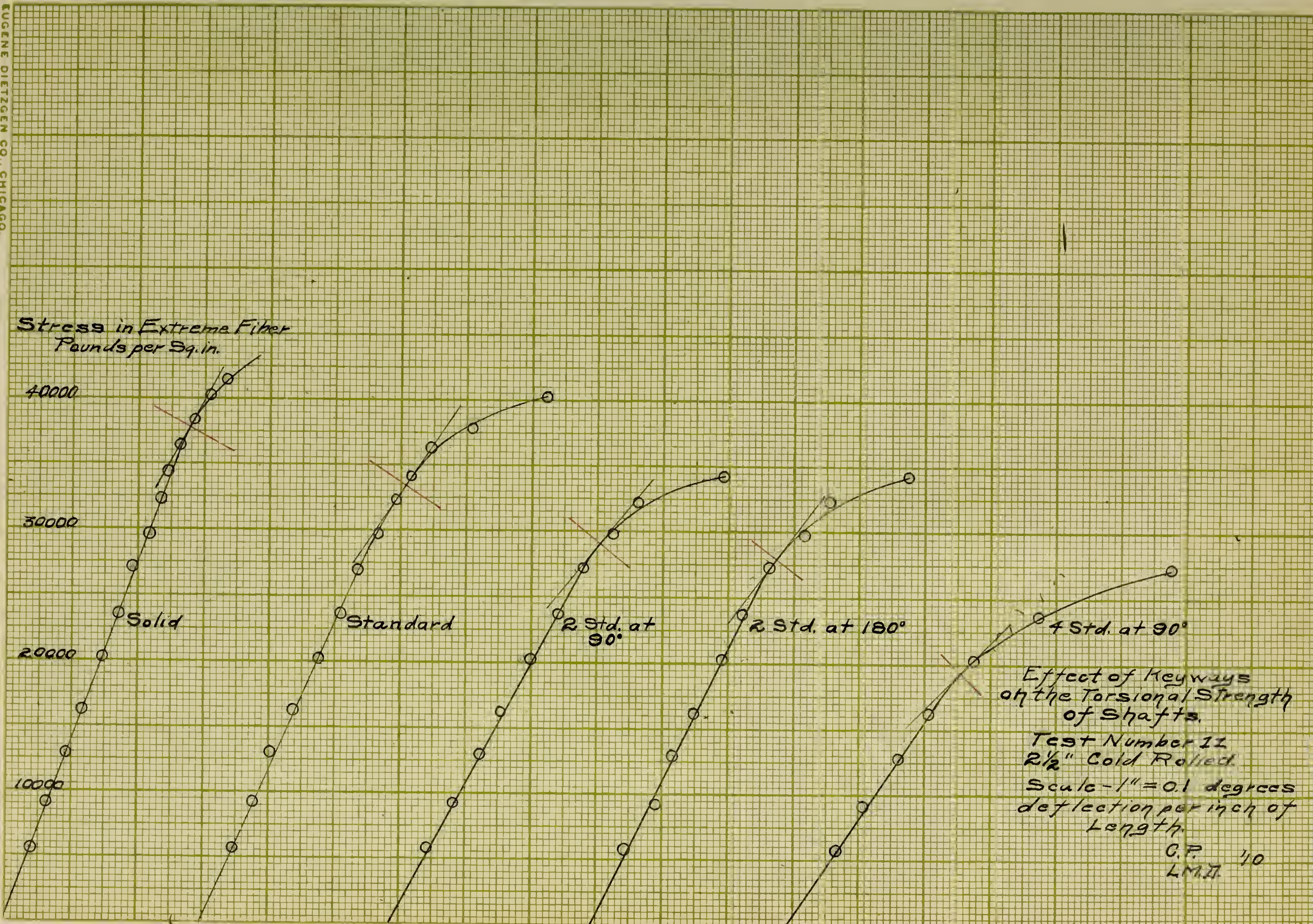

Stress in Extreme Fiber
Pounds per Sq.in.
30 000
20 000
10000
Solid
One Direction
Round
Flat
Standard
Effect of Keyways
on the Torsional Strength
of Shafts.
Test Number 8.
2"(1 15/16" actual) Turned.
Scale - 1" = 0.1 degrees
deflection per inch of
Length.
C.P.
L.M.D. '10

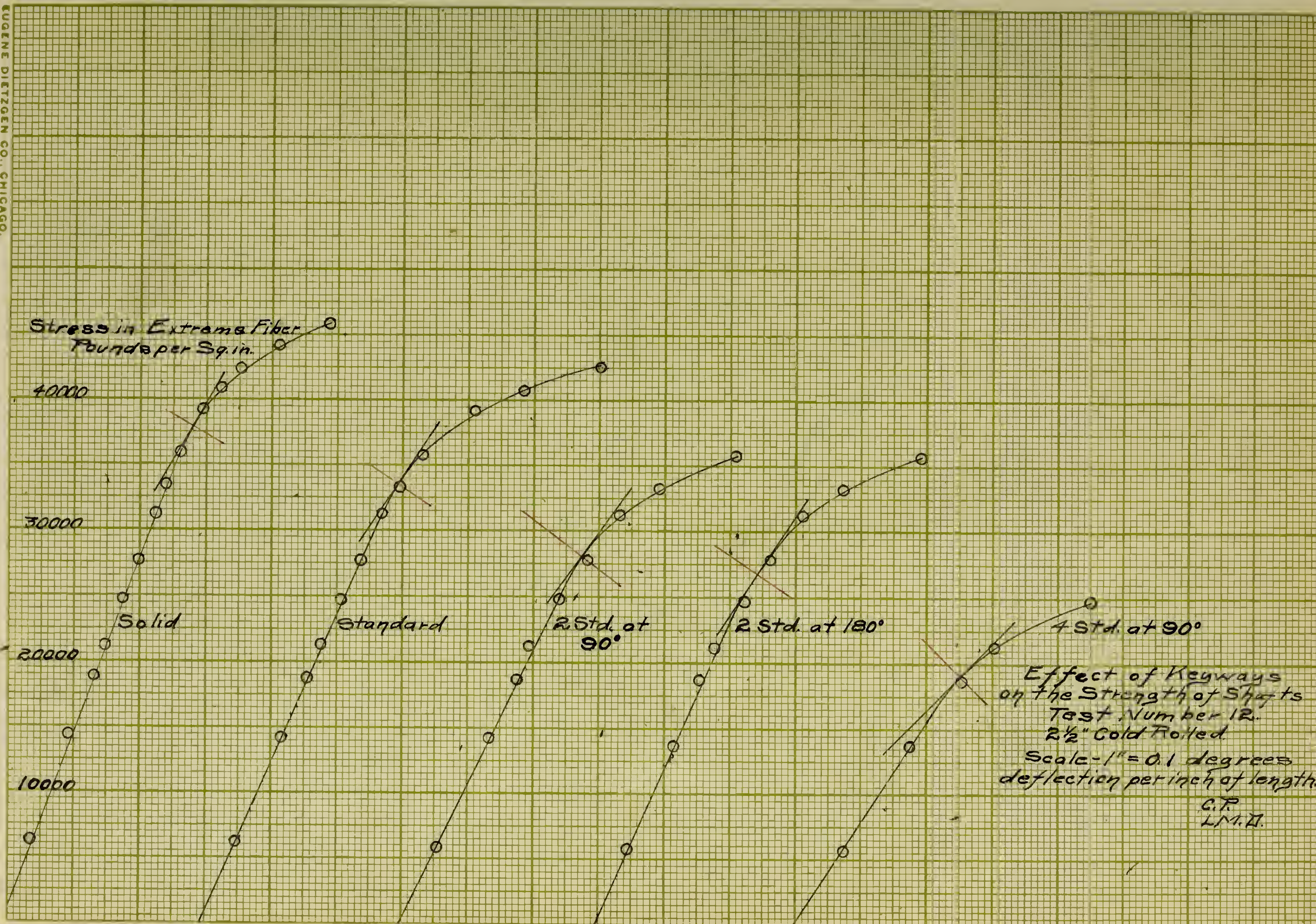


EUGENE DIETZGEN CO., CHICAGO.

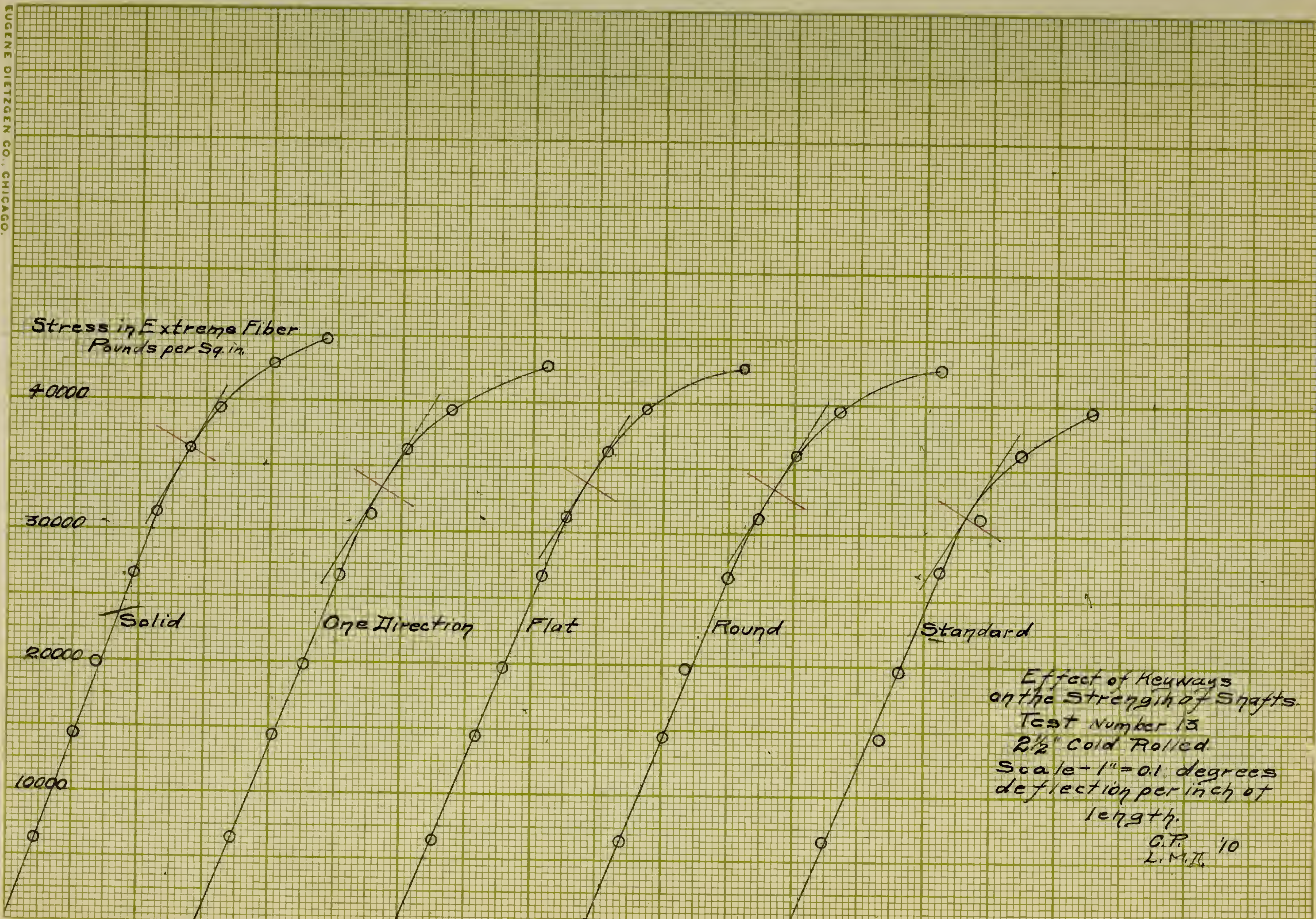


Stress in Extreme Fiber
Pounds per Sq. in
40000
30000
20000
10000
Solid
Std. Long
Deep
Effect of Keyways
on Torsional Strength of
Shafts.
Test Number 10
2½" Cold Rolled.
Scale - 1" = 0.1 degrees
deflection per inch of length.
C.P.
L.M.D. '10

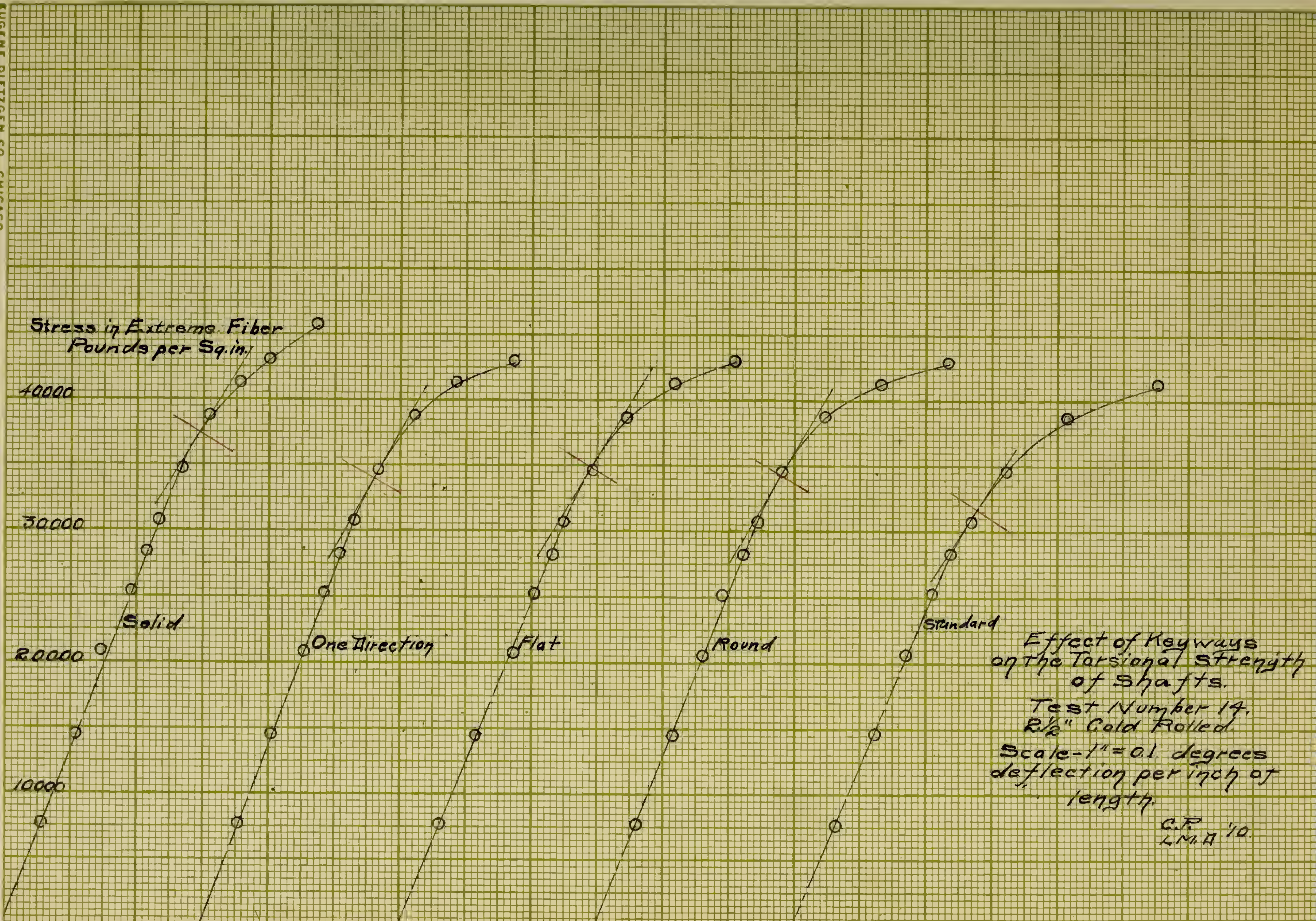

Stress in Extreme Fiber
Pounds per Sq. in.
40000
30000
20000
10000
Solid
Standard
2 Std. at 90°
2 Std. at 180°
4 Std. at 90°
Effect of Keyways on the Torsional Strength of Shafts.
Test Number 11
2½" Cold Rolled
Scale - 1" = 0.1 degrees deflection per inch of Length.
C.P.
L.M.II
'10



Stress in Extreme Fiber
Pounds per Sq. in.
40000
30000
20000
10000
Solid
Standard
2 Std. at 90°
2 Std. at 180°
4 Std. at 90°
Effect of Keyways
on the Strength of Shafts
Test Number 12.
2½" Cold Rolled.
Scale-1" = 0.1 degrees
deflection per inch of length.
C.P.
L.M.D.



Stress in Extreme Fiber
Pounds per Sq. in.
40000
30000
20000
10000
Solid
One Direction
Flat
Round
Standard
Effect of Keyways
on the Strength of Shafts.
Test Number 13
2½" Cold Rolled.
Scale - 1" = 0.1 degrees
deflection per inch of
length.
C.P. '10
L.M.K.


Stress in Extreme Fiber
Pounds per Sq.in.
40000
30000
20000
10000
Solid
One Direction
Flat
Round
Standard
Effect of Keyways
on the Torsional Strength
of Shafts.
Test Number 14.
2½" Cold Rolled.
Scale - 1" = 0.1 degrees
deflection per inch of
length.
C.P.
L.M.A. '10.